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# THE MANGANESE DEPOSITS OF POSTMASBURG, SOUTH AFRICA.

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CONTENTS.

Introduction ..... 95
Geological Structure ..... 98
Features Indicating Replacement ..... 104
The Process of Replacement ..... 107
Ores ..... 114
The Diastrophic Aspect ..... 117
Mining ..... 120
Bibliography ..... 122

## INTRODUCTION.

THE manganese deposits of Postmasburg, which have attracted a great deal of attention, were discovered by Capt. T. L. H. Shone in 1922, and are situated close to Postmasburg in the Cape Province (Lat. 28° 20′ S.; Long. 23° 04′ E.) some 120 miles to the northwest of the diamond mining center of Kimberley, with which they are connected by rail. The distance from the two nearest harbors, East London and Durban, is 643 and 743 miles, though for traffic reasons export has been through the latter port.

The ores have originated on or near the junction of the Campbell Rand dolomitic limestone and its unconformable covering of Matsap Beds, and are closely associated with equally extensive hematitic deposits within an area 40 miles long by 9 miles across.

The first detailed account, by Dr. A. L. Hall of the Union

Geological Survey, in 1926, showed the sheet-like character of the deposit and the persistence of the ore horizon; also the high grade of much of the product and the vast quantity of ore present was indicated. It was concluded (3, 38) [1] that "the ore is sedimentary in origin, and due to replacement of argillaceous material through the circulation of manganese-bearing solutions, rather than a result reached already during the period of deposition." Although there has since been general agreement as to the considerable tonnages present, the somewhat complicated nature of the deposits and associated rocks has called for various interpretations of their origin.

In 1928 the author (1, 36) showed that the ore-bearing "zone" was more variable than had been supposed, that it did not occupy the same horizon everywhere, and that the bodies could be regarded as "colloform" deposits replacing sediments of different types, the manganese having in the main taken the place of previously introduced iron, both substances having been derived from the subjacent dolomite. Although the close connection with tectonic disturbances was pointed out, that aspect has never received due recognition, therefore the diastrophic rôle will be stressed here.

In 1929 appeared the Geological Survey Memoir by Dr. L. T. Nel (6), in which the problems of genesis and mining were admirably discussed and the present writer's contentions in the main upheld, abundant evidence of metasomatic replacement being cited. Last year the writer was able to profit by the numerous new sections disclosed through mining operations, and feels that it is now possible to speak with more confidence about the behavior and genesis of these extensive and instructive deposits.

During a late stage in the preparation of this paper there became available two publications in which, on the contrary, a syngenetic origin was advocated. In the first of these Prof. E. Kaiser (4, 734–5) strongly doubts the feasibility of replacement of such a narrow zone over so extended an area, but does not give

[1] Numbers in parentheses refer to bibliography at end of article.

sufficient detail in support of his views. The second, by Prof. H. Schneiderhöhn (8), is a penetrating mineralographic study based upon hand specimens—the first of its kind on these deposits—and is illustrated by many fine photomicrographs, the several manganese minerals and their paragenesis being admirably dealt with. Many of his deductions can be accepted, including the view that the deposits display epi- to meso-metamorphism, but his conclusions that the ores were deposited originally as fine-grained manganiferous sediments is at variance with field observations, though the study as such is an outstanding contribution.

The region forms open, flattish country standing at an altitude of between 4300 and 4400 feet generally, from which rise isolated rocky hills or chains for a further few hundred feet or so. The mean annual rainfall is just under 15 inches.

As shown in Fig. 1, which, however, does not cover the entire area, the deposits constitute two symmetrically set "belts" linked at their ends, which are merely erosion-relics of a formerly much greater whole:

(1) The *Western,* which, as the Gamagara Ridge, trends northerly for 40 miles, with the ore zone reposing mainly on the dolomite, and dipping westward, with subsidiary folding, beneath the Matsap quartzites until it is cut off by the parallel Gamagara Fault. (2) The *Eastern,* which more precisely consists of an arcuate chain of outliers, the Klipfontein Hills, rising from a plain of dolomite.

Included admittedly in the tracts designated "ore zone" is a large proportion of barren or very low-grade material, but the amount of commercial ore present therein is unquestionably enormous. Only the more accessible southern portion has been tested, although the northern is also productive. With the exception of a central section held by the Gloucester Manganese Co., practically the whole of the Western Belt belongs to the Manganese Corporation and has been actively developed by them. Ore was exploited on a considerable scale during 1930–31, but owing to the world-wide depression and to Russian competition, operations were suspended late in 1931. The South African Man-

ganese Co. owns and has tested the southern part of the Eastern Belt, but has not yet exported; it possesses huge deposits of hematite ore as well.

The author has to thank these companies for permission to

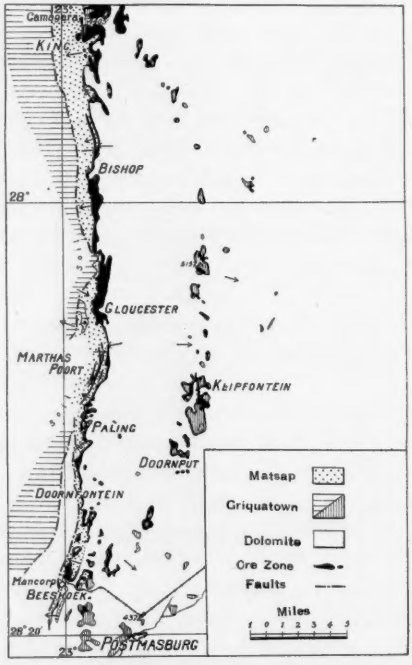


FIG. 1. Geological map of the Postmasburg manganese fields. Adapted from L. T. Nel.

examine their properties, and Professor R. B. Young of Johannesburg and Dr. L. T. Nel of Pretoria, for assistance in the preparation of polished specimens.

## GEOLOGICAL STRUCTURE.

An apparent simplicity is belied by closer acquaintance, the formations primarily involved being the following, in descending order:

B. *Matsap System* (Gamagara Beds)—probably early Palaeozoic.

4. Pale quartzites.

3. Basal beds of variable character.

*Erosion period and unconformity.*

A. *Transvaal System*—late Proterozoic or early Cambrian.

(2) Lower Griquatown Beds—banded ferruginous slates with a locally developed hematitic facies at its base, the Blinkklip Breccia 2a.

(1) Campbell Rand dolomite, having the "chert zone" at its summit.

The mineralization, which was very extensive, belongs to two periods, widely separated both in time and character: the *earlier* one pre-Matsap, shallow-seated and *ferriferous;* the *later,* post-Matsap, formed at intermediate depth and dominantly *manganiferous,* the ores consisting mainly of psilomelane, braunite and sitaparite.

1. The basement dolomite consists of a great thickness of gray to bluish bedded dolomites and limestones weathering with a gray, yellow, brown or black crust, which contain iron and manganese in the form of carbonates to the extent of from 1–4 per cent. (total), a feature vital from the metallogenetic viewpoint. Silica is abundant as bands, lenses and veins, and builds at the very top of the formation a zone of chert that is persistent throughout the region, being usually sharply defined from the succeeding Griquatown Beds, though known to interdigitate therewith in one area. It outcrops in hummocky masses with little sign of bedding, and is normally white to gray with a peculiar brecciated structure, especially near or at its summit. Over the Fields it has been extensively recrystallized and has locally been further brecciated and replaced by manganese oxide. This gives it a speckled appearance and it is known as the "Marker." Usually less than 50 feet thick, it reaches 250 feet on Doorn Put, but over a good deal of the Western Belt, save at either end, it is present as mere remnants, or is absent through erosion, a

matter of great importance in the corresponding development of the ore zone.

2. *The Griquatown Ironstones,* conformably succeeding, appear in outcrop as yellow, brown, reddish, blackish or white, banded slaty strata with cherty and ferruginous layers alternating, certain bands of which are rich in magnetite, hematite, or limonite—banded ironstones, in fact. Within the limits of the Fields these rocks and also still higher beds were all but removed by pre-Matsap denudation, and the majority of the remnants converted into hematitic varieties that grade up into that remarkable type, 2a, known as the Blinkklip Breccia. Such erosion was connected with the arching up of the strata and consequent exposure of the dolomite along a N–S axis, and was accompanied by an important fracture, which determined subsequently the westerly limit of the Western Belt.

2a. *Pre-Matsap Mineralization.*—Certain borings and mine workings prove that the visible exposures of the ironstones are merely the intensely oxidized and silicified products of parent strata, which in depth are no longer yellow or red rocks, but whitish, gray, greenish, bluish or black shales, silt stones and cherts. Certain of them carry soda in the form of the amphibole crocidolite, some potash even, and the darker and heavier varieties are rich in iron, as ferrous silicate, in these respects strongly recalling certain of the Lake Superior iron-bearing formations. The bulk of the observed alterations must have taken place during the period of sub-aerial erosion—coupled with moderate folding—of pre-Matsap times (early Palaeozoic), under rather peculiar climatic conditions presumably.

Such action was enormously stimulated wherever sub-surface solution of the underlying dolomite led to the collapse into hollows of the ferruginous Griquatown basal beds, to their fracture, and to the replacement of the siliceous matrix in the shattered masses by iron brought in by solutions. As Rogers (7; pp. 174–78) has shown, every transition can be found from undisturbed, regularly-bedded ironstones to minutely shattered strata having the fragments cemented by secondary hematite and

specularite, together with a little quartz. Wherever the succession permits inspection, the basal parts of such masses are found to have sunk deeply, with tilting, into the supporting, though only slightly disturbed dolomite; in the upward direction the amount of fracturing becomes progressively less. The author has suggested also that some of the shattering may have been effected by forces set up during the crystallization of the hematite within incipient fissures, a process termed "crystallization-brecciation." Owing to erosion, the full thickness of the breccia is seldom measurable, but up to 50 feet is not unusual, and 200 feet has been recorded.

Huge masses of such secondarily-enriched hematitic rocks, embracing enormous deposits of high-grade iron-ores, cap the hills of the Eastern Belt and are also represented at either end of the Western one. Presumably the iron was introduced as goethite and thereafter dehydrated, but signs of shrinkage are not clearly to be made out.

3. *Matsap Deposition.*—After reduction by sub-aerial erosion to a plain of dolomite carrying low ridges and knobs of chert, banded ironstone or Blinkklip breccia, and having occasional sink-holes—a karst landscape in fact, just like the present one—, the area became submerged. The basal beds of the Matsap (Gamagara) laid down thereon vary considerably not only in thickness, but lithologically, from point to point. Next, is a group of argillaceous beds generally less than 120 feet thick, usually aluminous, often highly so, and carrying up to 42½ per cent. of $Al_2O_3$, the matrix consisting mainly of kaolinite and what the writer regards as pyrophyllite, and a little mica. Diaspore in dark platy crystals, outwardly resembling ottrelite, is a conspicuous constituent, and occasionally, as shown by Nel (6), the rare mineral zunyite. Oolitic, pisolitic and organic structures are present, as detailed by Schneiderhöhn (8, 718). Without doubt these finely bedded shales represent transported bauxitic clays from the prolonged weathering of a peneplaned terrain of dolomite or of the andesitic lavas of the Middle Griquatown Series, a group present quite close at hand.

At or near their base, but in places up in the shales, is a conspicuous bed—the Doornfontein or Gamagara Conglomerate. Its composition and thickness vary much from point to point. It contains chips and sub-angular to well-rounded pebbles of pale or jaspery chert (from the top of the dolomite), of vermilion jasper, of normal ironstone and of the hematitized breccia, and is indeed in places crowded with inclusions of the two last formations, which are set in a reddish, excessively fine-grained matrix. The original binding material is not often seen, for over wide areas this conglomerate, and with it the associated shales, has suffered intense metasomatism and has been replaced by hematite or manganese oxides, as detailed below.

4. The succeeding pale *Matsap Quartzites,* that overlie the shales and attain a huge thickness a little farther to the west, require no comment, save that they form along the entire Western Belt a neutral covering to the ore zone.

5. *Post-Matsap Folding and Metasomatism.*—The intense folding of the Matsap Beds, finely seen in the region to the west, extended into the fields in subdued form. In the Western Belt the strata are traversed by foldings usually arranged *en échelon* and at angles more or less oblique to the belt itself and also to the important N–S faults and thrusts that bound the ore zone on its western side. This folding is strongest in the central section, that is to say between Bishop and Paling, and indeed on Martha's Poort the dips are steep and occasionally reversed (Fig. 2). Throughout this section a small-scale, down to microscopic, folding and faulting is also to be noticed. Towards the two ends thereof, and in the Eastern Belt generally, dips are low, but with occasional inflections (Fig. 3).

The *Second Period of Mineralization* has to be connected with this diastrophic episode and, so far as can be made out, with its initial phases; unlike the first one, however, it involved *manganization as well as hematitization.* This mineralization affected portions of the strata intervening between the top of the dolomite proper and the base of the quartzites, and replaced by means of oxides of iron and manganese such diverse materials as dolomite

(rare), chert, banded ironstone, Blinkklip breccia, Matsap conglomerate and shale.

It must be stressed that the ore horizons as seen in the two belts represent parts of one great development, severed since by erosion, as Kaiser has indeed admitted.[2] Viewed in the gross the

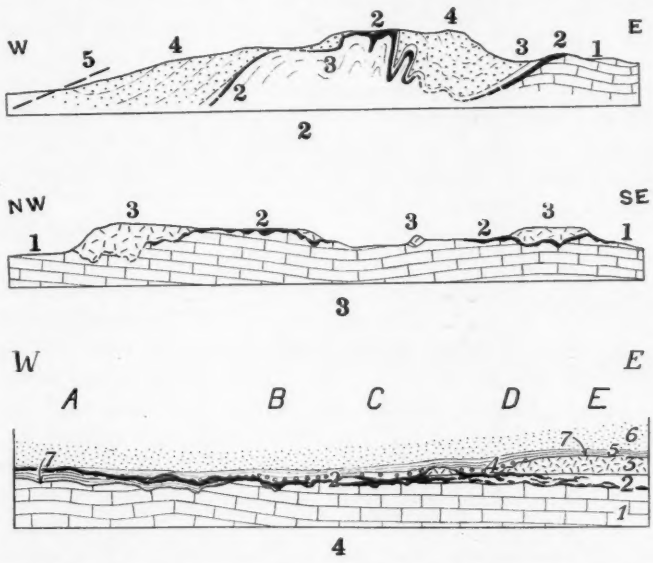


FIG. 2. Section, just over one mile long, across Western Belt on south side of Martha's Poort. 1, Dolomite; 2, Ore zone; 3, Matsap shales; 4, Matsap quartzites; 5, Thrust-plane (?).

FIG. 3. Section, 2 miles long, across Eastern Belt, through the Klipfontein Hills (after Nel). 1, Dolomite; 2, Chert breccia carrying ore; 3, Blinkklip breccia.

FIG. 4. Schematic section (not to scale) showing the transgressive behavior of the ore zone (black). *A*, Martha's Poort; *B*, Palong; *C*, Beeshoek; *D*, King and Doornput; *E*, Klipfontein: 1, Dolomite; 2, Chert; 3, Blinkklip breccia; 4, Conglomerate; 5, Shales; 6, Quartzite; 7, Inter-formational unconformity.

[2] (4) 7, 729, 734; see also p. 733 for an admission as to the variable nature of the hanging wall.

ore zone *cuts definitely across* not only the stratification of the two systems concerned, but an important unconformity between them. In the east it occupies a position well within the chert, in certain places a hundred feet or more below the base of the Matsap; at either end of the Western Belt it passes along and through the unconformity, but in the central portion, it ascends into the Matsap System, attaining its highest level on Mogoloring, where at one spot it is in direct contact with the quartzite roof, with fully 150 feet of pale shales below it at Martha's Poort. Such behavior is shown in Fig. 4 (with subsequent folding ignored), and effectively disposes of the view that the zone represents a syngenetic body. Hence it is unnecessary to combat that hypothesis in detail.

In places, the replacement is localized and patchy, as is commonly the case with the massive chert bed 2 (marker), but in the more fissile strata there is a remarkably persistent zone of mineralization ranging in thickness up to over 100 feet in places, and giving rise to a rudely tabular, pseudoconformable body running along the Western Belt for fully 35 miles, as delineated on the excellent geological map by Nel. Over considerable stretches the manganiferous portion passes upwards through manganiferous hematite into a hematitic horizon above. Where it rests upon (dissolved and weathered) dolomite, its footwall is sharp, though irregular; in other places there is a more or less indefinite passage into barren or incipiently mineralized rock. It is indeed difficult under such circumstances to cite average figures for the thickness of the ore body itself, but in general it ranges around 25 feet, though that may be exceeded locally. Naturally not all of this is mineable material.

### FEATURES INDICATING REPLACEMENT.

Both Kaiser (4, 736) and Schneiderhöhn (8, 723) conclude that the manganese and iron were accumulated primarily in the aluminous Matsap shales, but to the writer there does not appear to be anything in the latter's excellent study to contradict an epigenetic hypothesis. Assuming that these muds were rich in

compounds of Mn and Fe, the latter must, in order to explain the field relations, have originally been disseminated through the sediments in an extraordinarily erratic and arbitrary manner, a view totally at variance with the finely bedded nature of those rocks. We should furthermore have to postulate a wholesale re-solution and migration of the oxides, in which connection the relative insolubility of those substances as compared with the parent carbonate rock should not be forgotten.

On the contrary the base, middle, or top of this shaly group can be seen in various localities on the fields, still in a wholly unmineralized state (at most only reddened by ferric oxide, the color being dominantly white, cream or terra-cotta), carrying a little clastic mica and, in places, diaspore as a metamorphic mineral. The features collectively indicate argillaceous sediments primarily rich in alumina, poor in iron and practically free from manganese, which strata became at a subsequent date selectively mineralized.

Furthermore the syngenetic hypothesis entirely fails to explain the deposits of the Eastern Belt as a whole.

Although for miles along the Western Belt the ore zone rests directly upon the dolomite, good natural sections across the contact are rare. Trenches on Doornfontein (B) show small veins of solid ore, and diffusions, descending into the massive dolomite, whereas the deep soil above is charged with lumps of coarsely crystalline ore much of which has been released by the sub-recent solution of the enclosing rock. Though such ore is of high grade, it carries somewhat more silica than usual and, suggestively, the contiguous dolomite has been silicified in spots. The influence of mineralizing solutions is indicated in the very top of the dolomite by seams and threads marked out by a coarser crystallization.

In the majority of the exposures of the Chert Zone in the Western Belt, and throughout most of the Eastern, replacement with recrystallization of that rock is conspicuous. Over the Fields the chert has developed a darker tint and a peculiar mottling due to irregular areas of pale or dark quartz, and ill-

defined patches showing rude agate-structure are not unusual. In this state it is easily recognized, being known as the " Marker."

In the mineralized portions thereof, the ore forms irregular bodies and ramifications, sometimes on a large scale, with ill-defined boundaries that fade into barren chert. Transitions are common from chert traversed by threads of manganese (Fig. 5), through curious ore breccias crowded with chert fragments (" sausage ore ") (Fig. 7) to solid ore dotted with blebs of glassy quartz and pitted with wad-filled cavities. Only rarely is the replacing mineral a manganiferous hematite. Silica is the chief gangue, and barite is fairly common, but, as should be expected, diaspore is absent. In some instances pits sunk into slightly darker areas of the chert outcrop have disclosed workable bodies of unknown extent; in others, mining has proved such ore to be pockety. In the cliff section, 250 feet high on Doorn Puts, the vertical and lateral variation of such replacements, isolated from one another by barren chert, can be studied.

The hematitic *Blinkklip breccia* has been found manganized at only a few places, but this is probably due to insufficient search along outcrops.

Replacement is obvious in the case of the Matsap fragmental rocks—Doornfontein Conglomerate—which range from conglomerates to breccias, the matrix being a pale to red mudstone, although it may be silicified in places. The transition laterally within a foot of such a pale cherty variety to one replaced by hematite has been observed on Beeshoek. Such hematized rocks, with the primary fragmental characters excellently preserved, are common along the Western Belt and form workable iron ores, but have in many places been partially or completely manganized and then constitute an integral portion of the ore body. The manganiferous solutions have first attacked the matrix, next the inclusions, and have finally obliterated all traces of original structure.

Replacement is naturally less striking in the case of the *Matsap Shales,* but numerous sections between Beeshoek and Paling show the individual ore bodies, or else the workable portions,

to be lenticular, to fork, and in places to transgress the enclosed little altered or unaltered strata. Interlamination with less altered shale is quite common near the top of the zone. Instances have been noticed—and such should become numerous as faces are opened up—where patches of little altered or unaltered reddish shales are entirely enclosed in the ore body, showing ragged and usually ill-defined margins, although sharp transgressive junctions have also been seen. Elsewhere, seams of slickensided pink shale are included that suggest original fault-clays, which had proved impervious to the mineralizing solutions. In Calvert's Cut on Beeshoek, for example, the workable body cuts nearly vertically across one side of a sharp monoclinal fold in shales. It is commonly difficult to decide the precise limits not only of the manganized portion, but of the workable body, in the various cuttings; contiguous trenches may show very different sections, a behavior inimical to systematic mining. Any attempt to predict the exact course of the pay-ores by applying principles based upon the syngenetic hypothesis is doomed to failure.

In a general way the ore zone is a compound one, rich in manganese below, and in iron above, though in a few places that order is reversed; the transition may be gradual or sharp. In addition to workable manganese ores, there are equally large amounts of highly manganiferous hematites as well as hematites.

### THE PROCESS OF REPLACEMENT.

As pointed out by the author in 1928, and arrived at also by Nel, the source of the manganese and iron lies unquestionably in the widespread underlying dolomite formation, which carries universally appreciable amounts of these metals as carbonates. The 18 analyses that are available for this region give a MnO content of 0.5–2.63 per cent. with a mean of 1.2 per cent.; the iron has only occasionally been returned separately, but is seemingly in comparable proportions. Wells or boreholes into this formation not uncommonly pierced pockets or seams containing wad or manganiferous mud, and superficial weathering has pro-

duced on it, near Krugersdorp in the Transvaal, mineable lateritoid manganese ores carrying some iron. The soils on the dolomite are invariably dark red or chocolate and rich in oxides of manganese and iron. Traces of phosphorus are of course present in that rock, and also sulphur as pyrite; the single sample analyzed for barium gave a blank. It is likely that the appreciable proportion of BaO in the ores was derived from this formation, although the Griquatown ironstones and volcanics are not excluded as possible sources.

Sub-surface solution of the dolomite of post-Matsap date, beneath the Marker even, can definitely be made out, and is probably more extensive than the outcrops would suggest. Thus on Paling, an incline begun in solid shale proved the ore zone below to become progressively more fractured as the underlying dolomite was approached. Nel has commented upon the amount of shattering displayed in many of the prospect workings. Such solution seems to have been particularly active next to the ore body, more especially where the chert zone had previously been removed by erosion. It is noteworthy also, that the ores are confined to the region wherein the Palaeozoic denudation had laid bare a core of dolomite, which was thereafter buried beneath Matsap sediments; where the succession from the dolomite upwards remained unbroken, such deposits were not formed. This serves to explain the great areal distribution of the ores—approximately 200 square miles—a fact which Kaiser (4, 734) has considered as incompatible with an epigenetic origin.

From his analyses, Nel has computed that 53.6 tons of dolomite would have been required to furnish one ton of ore, a calculation which seems more or less in accord with observation. Although in the nature of the case the full amount of such solution is but rarely calculable, there are a few spots where it must have exceeded 150 feet, but lesser values are measurable at many places. Manifestly, the roofing materials would have been the ones most liable to attack, which is in accord with the evidence given above, that the bulk of the mineralization was seemingly effected from below.

Meteoric waters were doubtless responsible, traveling along the unconformable base of the Matsap or along thrust planes, or else descending by fracture lines in the quartzite covering. The $CO_2$ required must have been derived from the air or from the reaction of humic acid upon the carbonate rock; with the oxi-

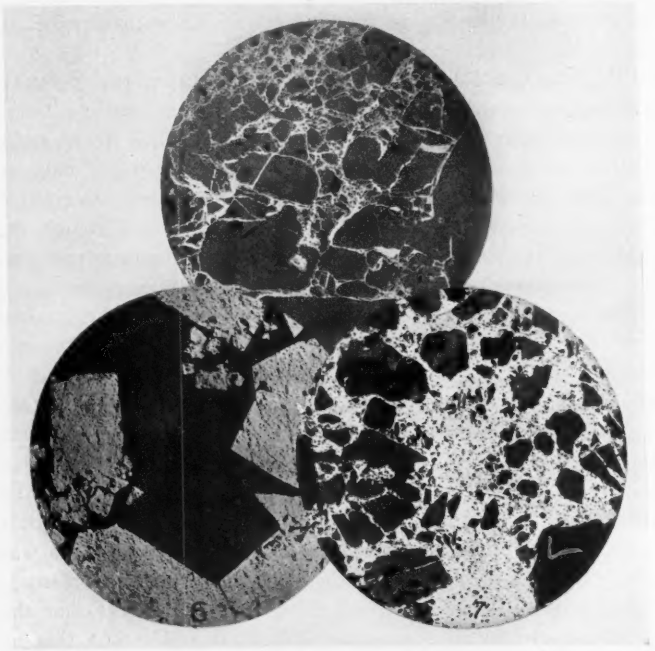

FIG. 5. Chert (gray) reticulated by manganese ore, probably sitaparite (white). Kapstewel. × 15.

FIG. 6. Coarsely crystalline ore showing porphyroblasts of sitaparite (white) and diaspore (dark). Magoloring. × 15.

FIG. 7. Relics of chert (gray to black) in manganese ore (white) Doorn Put. × 15.

dation of the solution some of this $CO_2$ would have been released for further activity. The presence of alkalies also is

indicated by ore analyses; such may well have been furnished by the Griquatown ironstones and volcanics. The bulk of the $Al_2O_3$ and $SiO_2$ set free must have escaped along with the bicarbonates of Ca and Mg by way of subterranean passages or through springs, the first-named most probably in the form of soluble alkaline aluminates. Some of the silica was, however, redeposited in the ore in combination with the manganese, or in druses.

The contrasted nature of the two mineralizations demands explanation because, although in each case the attendant solution of the dolomite must have furnished Mn as well as Fe, no manganiferous replacements of undoubted pre-Matsap age have so far been found. In those specimens of the non-mineralized Doornfontein conglomerate that were tested by the writer, the pebbles of banded ironstone and breccia gave no strong reactions for Mn, although more than traces were sometimes present.

The mineralization of the First Period was a pure hematitization, the enrichment in iron of the ironstones being brought about partly by the removal of silica, partly by the introduction of ferric oxide, mainly, it is presumed, by waters percolating downwards from the mass of weathering ferruginous strata above. Having been formed under a covering seemingly less than 500 feet thick, and hence under atmospheric temperature, these deposits must be regarded as entirely *supergene*. One has to conclude, therefore, that the manganese in the rising solutions was unable to produce replacement for physical and chemical reasons.

It has been demonstrated by Dieulafait and others that the bicarbonate of manganese is normally more stable than that of iron, therefore the manganese salt could well have escaped oxidation, whereas the iron was precipitated as hydroxide. It is known conversely, that at shallow depths Mn is liable to removal by leaching in preference to Fe. Colloidal $SiO_2$ may have furthered such separation, since silica-sol tends to precipitate ferric hydrosol; organic matters incidentally tend to stabilize such mixtures.

During the Second Period, on the contrary, the formations,

judging from the huge thickness of the Matsap beds measurable only a few miles to the west, were deeply buried. A temperature above normal for the reacting zone must be postulated. This view is supported by the abundance of diaspore as tiny gray or blackish patches or plates in the non-replaced aluminous shales, and as prismatic aggregates up to inches in length in certain of the ores, where this mineral is characteristically manganiferous and pink or red, and a rose-pink soda-rich margarite (ephesite) is occasionally present. The specularite veins in the quartzite roof provide corroborative evidence. As Schneiderhöhn has emphasized, an appreciable metamorphism is indicated petrologically. A high temperature is, however, negatived by the colloform nature of the ores, though it is known that opal can be deposited at between 100° and 200° C. Heat would have promoted the solution of $SiO_2$ by carbonated waters and would presumably have aided the precipitation of manganese as hydroxide. The deposits are regarded, therefore, as belonging to the middle depths, or, as Schneiderhöhn has put it, to the *epi-* or *meso-zone*. The writer considers them as *hypogene*. The rôle played by earth movements is dealt with in the sequel.

The eclectic hypothesis postulates the permeation into a covering, in which bending and fracturing were in progress, of warm waters carrying bicarbonates of Ca, Mg, Fe, Mn, Na and K, silicic acid (the silicates would probably have been hydrolized) and compounds of Ba, P, and S. The roof can be viewed as a semi-permeable membrane, that is to say, it would readily have been penetrated by electrolytes and gases, although only slowly by colloidal bodies. That the ferric hydroxides seem to have been imperfectly colloidal under such conditions of temperature and pressure is suggested, (*a*) by their greater mobility (thin seams of specularite being present in the quartzites to a distance of hundreds of feet above the base of the latter); (*b*) by the dominance of hematite in the upper half of the ore zone; and (*c*) by perfect pseudomorphism of clastic structures in the hematitic replacements, for, when solids are replaced by gels, the ordinary laws of volume usually do not hold. In contrast, the

replacement of the newly precipitated compounds or of the fresh rock material by manganese and silica gels brought about partial to complete obliteration of original structures with appreciable changes of volume. Such is in part explicable by the fact that the oxides of Fe and Mn are not isomorphous, although the carbonates are. It is admittedly curious that the hematitic Blinkklip breccia should have been manganized only sporadically, though such failure may have been due chiefly to the physical condition of the ferric oxide which had mostly been formed during the earlier period of mineralization. The problem is certainly complex, as shown by Wagner's (11, 180) observation that the hematite in these breccias is of two distinct kinds, while Schneiderhöhn (8, 709) has noted the same thing in some of the manganese ores.

The soft colloidal manganiferous aggregates can be conceived as normally packing in the lower part of the replacement zone as in a filter, the accompanying or displaced ferric hydroxides being largely passed on to higher levels and so producing the bi-zonal arrangement found. In a general way, the richest ores of manganese tend to occur near the bottom of the zone, particularly where dolomite forms the footwall. Fracturing due to unequal subsidence would, however, have enabled the colloidal manganese hydroxide to ascend at such places into the middle or upper levels and so reverse the usual order. In the chert zone the two-fold character is less marked and the hematitic facies is poorly developed or absent. As would be expected, the cherts and conglomerates have been more readily replaced than the shales, for colloidal materials, such as clays, are not easily penetrated by other colloids, wherefore the selective metasomatism of the dominantly argillaceous beds. It would seem not at all unlikely that a highly important factor was the remarkable property possessed by manganese oxide of precipitating manganese from solution by catalytic action, as pointed out by Zapffe (12, 824), a process that would have led to segregation of the manganese.

Shrinkage of the mass through dehydration and molecular rearrangements is not manifested by the ferriferous types, but

is prominent in the manganiferous ones, as evinced by banded structures and by the characteristic irregular cavities ranging from microscopic pores to spaces several inches across, either empty, filled with wad or barite, or lined by opaline silica. Not infrequently such silica builds casts that now make a loose fit in the mold, indicating a still further contraction of the matrix. The crystallizing out of denser braunite from ore rich in psilomelane and its conversion into sitaparite would also have caused shrinkage. In such molecular rearrangements, mass-action would doubtless have played an important part. Fracturing and shearing in the zone are revealed by veins and threads of manganese minerals that cut the ore body, and by brecciaform structures therein.

The barite, which forms a rather constant associate, may be coarsely crystalline in the druses, where it tends to be molded on crystal faces of braunite. Such late crystallization finds its explanation in the fact that alkaline bicarbonates with $CO_2$ can hold barium in solution, notwithstanding the presence of sulphates (5, 105). Much of the Ba, however, and doubtless the K, Na and P also, is in a state of combination with the Mn oxides.

*Petrological.*—The chief foregoing points can be illustrated by means of polished surfaces, although these will hardly compare with the fine photographs published by Schneiderhöhn. The replacing of chert along irregular fractures, by sitaparite apparently, is shown in Fig. 5, which is from a specimen kindly loaned by Nel; Fig. 7 illustrates a more extensive shattering of this material, the envelopment and permeation of the fragments by manganese, mainly psilomelane, with progressive recrystallization of the pale parent chert into darker quartz. In a specimen taken from the Marker on Doorn Put, crystalline ore is set in a black, horny silica-gel and shows occasional crystal outlines against the latter. The silica is practically opaque through disseminated manganese, but in favorable situations, where the material is translucent, the foreign matter is seen to send out into the isotropic gel delicate brown-black threads or needles, which appear to consist of manganite.

The impregnation (shown in polished surfaces) of reddish shales by psilomelane is well marked, following principally the bedding-planes, such ore being in turn cut by veinlets of crystalline pyrolusite, which are parallel to the stratification, but cross it in places; small idioblasts of sitaparite make their appearance in the massive replacement product. The specimen of Doornfontein conglomerate was studied because of its partial manganization. All stages in the process of hematitization are displayed by its rounded to flattened inclusions, which range from soft ocherous slate to solid banded ironstone. Although the matrix has been largely, and in some parts completely replaced by manganese, mainly as braunite and sitaparite, the variably hematitized pebbles have only been incipiently manganized, and their boundaries remain sharp. By treatment with hydrogen peroxide (9, 484; 10, 115), one finds that any such alteration has proceeded along their exteriors and following certain laminae. In other portions of this conglomerate, immediately alongside, the metasomatism has been more intense, the original fragmental structure all but destroyed, and the rock converted into a commercial ore.

The most highly metamorphic type is illustrated by Fig. 6 from a specimen prepared by Nel, the writer's examples thereof being too coarsely grained. A red diaspore (dark) occupies spaces between large porphyroblasts of sitaparite (pale), and in the angles between, occur smaller grains of diaspore, braunite and psilomelane. In other samples from this spot the original bedding is clearly indicated by parallel streaks of purplish altered shale in process of replacement by psilomelane, which alternate with more thoroughly recrystallized layers certain of which contain disaspore in larger crystals or more abundantly; that this represents the stratification is confirmed by the quarry sections. The phenomena suggest the development of the braunite and sitaparite from psilomelane.

### ORES.

As pointed out by Hall and Nel, two main types of ore are present: (*a*), a gray to black amorphous or cryptocrystalline kind

with occasional banded, botryoidal or drusy structure, and with a specific gravity as low as 4.3; and (*b*), a glittering steel-gray to blackish, finely to coarsely crystalline kind in which pyramidal to pseudo-cubic faces may be recognized, the specific gravity ranging from 4.8 to 5.0. In *a*, psilomelane predominates, while much of *b* agrees well with braunite, though Schneiderhöhn has shown that the Indian mineral sitaparite (2, 49) is also represented, building the larger crystals. The ore mined is a mixture of *a* and *b*, commonly an intimate one, with the relative proportions varying greatly even in different parts of a hand specimen, though in particular quarries one kind may predominate.

Schneiderhöhn (8, 704) has overstressed the distinction between the ores of the two belts, as can indeed be gathered from his own account; such differences as are noticeable are due primarily to the nature of the rocks replaced, although sitaparite is scarce because pressure and temperature were seemingly lower. The so-called "eastern type" is, for example, to be found in the western belt wherever the "Marker" forms the host, for instance over considerable distances along the northern section thereof and in the south on Beeshoek. The type in question is devoid of diaspore, since that mineral could develop only from aluminous shale, and is indeed characteristic of the folded section of the western belt, between Bishop and Paling.

As the paragenetic scheme deduced by Schneiderhöhn (8, 705) includes not only metamorphic, but pre-metamorphic manganese minerals, some slight modification thereof is demanded when an epigenetic origin is postulated. With such amendment the ore-mineral transformation would normally be:—manganese gel → "psilomelane" → pyrolusite and polianite → braunite → sitaparite —which is suggestively in the order of increasing density. The derivation of sitaparite from braunite would need the removal of $SiO_2$ and the addition of $Fe_2O_3$, and Schneiderhöhn (8, 709) has shown that the latter has been furnished by tiny inclusions of hematite in the braunite. Like the minute flakes of mica, they are set roughly parallel to the bedding of the parent shale and are regarded by him as marking layers primarily richer in iron,

but by the author as laminae selectively impregnated by ferric hydrosol, which is in process either of expulsion or of absorption into the new-forming manganese mineral. The transformation would require the elimination from the braunite of most of its silica. The clayey matter, on the other hand, became recrystallized into diaspore (mainly) and soda-margarite (rarely). It is clear that in the progressive enrichment of the ferruginous manganese ores or in the manganization of the Blinkklip breccia or Gamagara conglomerate with their hematitic inclusions, most of the ferric oxide so set free must have been passed up to higher levels to give rise therein to hematitic impregnation and ores.

Under metamorphism the structure of the ore has changed progressively from amorphous to coarsely crystalline, though even in the latter all traces of the bedding of the replaced rock, where such was shale or conglomerate, have not always been obliterated. In the braunite-rich varieties, that mineral is commonly xenoblastic to idioblastic, but the most highly altered types carry porphyroblasts of sitaparite and diaspore—significantly both small-volume minerals (Fig. 6). Although Schneiderhöhn (8, 715, 723) holds that there are no signs microscopically of internal stress-movement, it should be emphasized that the triple or quadruple recrystallization of the manganese compounds deduced by the microscope could be anticipated to have masked any such action, since it is in a sense analogous to the annealing process in metallurgy.

The above mineralogenetic picture is doubtless more simple than the truth. Each paramorphism must have brought about its corresponding shrinkage in volume, and, owing to repeated fracturing of the ore zone by subsurface solution, fresh colloidal compounds of Mn and Fe together with $SiO_2$ and Ba must have been introduced intermittently. The recorded presence of younger growths of psilomelane, pyrolusite and wad, more especially within cavities, thereby finds a ready explanation.

Hall and Nel have pointed out that the low proportion of sulphur present (about 0.05 per cent.), is wholly insufficient to fix the barium, indicating that most of that element is in chemical

combination in the manganese minerals; this also seems to be the case with some of the silica and the small amount of potassium that is present.

A characteristic and valuable property of the ores is their extremely hard, massive and more or less crystalline structure, the material being in the main harder than steel. The cavities form a fraction of the total bulk and are either empty or partially or completely filled with wad or barite, more rarely with opal. An incipient greenish sheen accompanied by mottlings of wad signals a lower grade, as does also a fissile structure in the finer-grained types that have commonly arisen from shales. Where relics of conglomeratic or brecciaform structures are detectable, the proportion of iron is almost invariably high. Where the parent rock has been chert, irregular blebs or patches of cherty silica or of recrystallized quartz are dotted unevenly through the massive ore, tending to give the material a curious brecciaform appearance (sausage-ore).

The content of metallic manganese in places exceeds 54 per cent., but commonly is less. Analyses of the various types have been published by Hall and Nel, which show that they are particularly low in S and P. Since these analyses have been based on small samples, the following bulk analyses of overseas shipments made by the Manganese Corporation during 1930–31 will be of value:

| % Mn | Mn | Fe | $SiO_2$ | $Al_2O_3$ | BaO | P |
|---|---|---|---|---|---|---|
| Over 52..... | 52.41 | 7.15 | 6.22 | 1.36 | 1.54 | 0.061 |
| 50 to 52..... | 50.93 | 7.65 | 6.02 | 1.60 | 1.78 | 0.073 |
| 47 to 49..... | 48.12 | 11.24 | 5.79 | 2.35 | 1.83 | 0.079 |
| 42 to 45..... | 43.87 | 14.91 | 5.59 | 2.21 | 2.48 | 0.088 |

The regular rise in the proportion of impurities with fall in the manganese content, save in the case of the silica, is noteworthy.

### THE DIASTROPHIC ASPECT.

The great areal development of the mineralization connects the latter with the post-Matsap orogenic movements of the region.

As shown by Nel, the Western Belt is bounded on its western side by what seem to be low-angle thrusts, along which the Middle and Lower Griquatown Beds and the Matsap—but little tilted—have been pushed eastwards over the Matsap quartzites that roof the ore zone. Cross-sections (e.g. Fig. 2) indicate that the foldings of the latter, and its relatively thin covering, must closely have underlain the Gamagara thrust, and their crumpling can be ascribed to the over-riding block.

Reference to Fig. 1 will show the striking geometrical, "bow-like" disposition of the preserved portions of the ore zone: the western "chord," having its supplementary foldings situated upon an arc concentric with that made by the eastern belt. Furthermore, at the two ends of the Western Belt the mineralization distinctly changes in its character to that typical of the Eastern one. Although the dip of the dolomite cannot always be deciphered because of deep weathering, it is noteworthy that the dips, where measurable, are commonly low, and that the two belts coincide roughly with gentle monoclinal structures affecting that formation.

The writer (1, 36) has suggested that the tectonic history of the area may be compared with that of the Swiss Jura, where upper competent beds, resting upon and moving over a shaly sole, were folded with but limited buckling of the massive strata beneath. At Postmasburg the varied strata from the ore zone upwards have been tilted and folded over large areas, whereas the supporting dolomite alongside shows only limited undulations. The "sole" in this case was constituted by the upper contact of the dolomite which suffered solution, so that the overlying beds, in adjusting themselves to the folding and solution of the basement, suffered considerable tilting and fracturing.

Puckering, together with thickening of the ore body, occurs along anticlinal axes, just as in "saddle reefs," and in one case erosion has laid bare the corresponding swelling along the trough. Nevertheless, despite such folding the zone—hematitic above, manganiferous below—displays a remarkable regularity, though, as stated earlier, it tends to alter appreciably its boundaries and

stratigraphical "horizon" along and across the strike. These, and other observations, suggest that the metasomatism was effected mainly during the earlier phase of crustal movement, the subsequent stages thereof bringing about the deformation of the strata and of the soft mineral replacements, the dehydration of the latter, and the crystallizing of new minerals therein. It can also be surmised that the circulation of waters in the dolomitic basement, and hence the positions of the principal solution-belts, were both influenced, if not governed, by the progressing deformation of the zone of replacement.

Metasomatism probably ceased with the termination of the folding and the subsequent erosion of the region in pre-Carboniferous times, but it is likely that minor additions and rearrangements of the Mn, Fe and Si continued, and may even be in progress today. It is instructive to note that in the dolomite territory loose pebbles and even the hard surface soil become coated in a few years' time with a dense patina of psilomelane through the evaporation of soil-water bringing up traces of manganese salts. As yet, no clear evidence has been obtained to support appreciable secondary surface enrichment, though in a number of places important accumulations of high-grade detrital manganese ores have been formed by the direct solution of the uppermost part of the dolomite and the release of its sporadic seams of primary ore. Schneiderhöhn (8, 713, 720) has detailed the secondary development of polianite, pyrolusite, psilomelane, quartz, and chalcedony, but it would seem more likely that some of these transformations really mark the final stages in the main mineralization and are not truly recent phenomena.

No close comparison can be made with any of the well-known deposits of the world, which in view of the unique set of circumstances attending the emplacement of the South African bodies, is hardly a matter for surprise. The writer has, however, drawn attention to a parallel with the Burnier and Rodeio deposits of Minas Geraes, Brazil (1, 31).

There can be no doubt that an intensive study of the Post-

masburg Fields, as they are opened up, will yield much information of great mineralogenetic importance. In the meantime it is freely admitted that the present contribution only touches the fringe of the various problems involved in these remarkable occurrences.

## MINING.

In the Eastern Belt, development has so far been confined to the several outliers between Doorn Put and Klipfontein, where the ores are practically restricted to the chert zone, the dip of which is commonly low (Fig. 3). As mentioned already, the deposits do not form a single bed, but a discontinuous series of partial or complete replacements of various horizons, a matter for surprise being the quantity of ore so frequently disclosed upon opening up what would casually seem almost barren ground. Despite the unpromising nature of much of the outcrop, good tonnages can be anticipated from this section, and not improbably from some of the other outliers further to the north. In places, a high Mn content is found, 59–60 per cent., and the ores are low in Fe and Al, but, as would be expected from their parentage, high in $SiO_2$, though S and P are both insignificant.

There are large amounts of hematite in the cappings of Blinkklip breccia, more particularly on the Klipfontein Hills. These, which were described by Wagner (11, chap. 11), are of Bessemer grade, with 65–69 per cent. Fe; 0.1–0.15 per cent. $P_2O_5$; and 0.2–0.3 per cent. S, the latter due to traces of pyrite.

In the Western Belt, development has been active over the nine-mile stretch between Beeshoek and Paling, where the beds replaced are chiefly Matsap, the workings having purposely been strung out so as to section the mineralized zone. Although a regular and persistent feature, the latter shows considerable variation in the degree of its mineralization from point to point, but appears to be mineable over the greater proportion of the outcrop within this section. It is surprising how much ore is present even in working faces that do not look promising. The ratio of ore to waste over most of this stretch can be taken as lying between 1 : 6 and 1 : 3.

Normally the ore grades upwards into hematitic types and the purity of the material can be determined to within close limits by the tint of the smoke produced during blasting; with increase of the iron content, the color changes progressively from black through chocolate to red. The percentage of iron is commonly higher than that of silica. Alumina is remarkably low, 1.3–2.3 per cent., which proves the thorough replacement and elimination of the dominantly argillaceous material, and furthermore shows that these ores are not mere lateritic muds, statically metamorphosed.

The extent of outcrop being so great, mining under cover will be unnecessary, exploitation resolving itself into quarrying with separation from the waste and the iron-rich varieties; the latter, though at present discarded, may in the future be used for making ferro-manganese. The zone is moreover accessible; dips at low to moderate angles westwards, save in the folded and hilly central section; and the water-table is deep. The ore is excessively hard, and averages 8 cubic feet to the short ton when solid, and about 13, when broken. At the central depot at Mancorp the ore is classified into four grades, crushed to lumps not exceeding six inches across, and railed to the 50,000 ton loading-plant at Congella, Durban, 743 miles distant. Freight charges account for the greater part of the costs of production.

Although development has shown the uncertainties involved in making close estimates on these fields, there can be no doubt as to the huge tonnages available even down to shallow depths, and, without considering the extensive area to the north of Paling or the Eastern Belt, the total reserves must furthermore be enormous! The output has hitherto been exported mainly to America and Japan, but negotiations are proceeding towards the establishment of a ferro-manganese industry on a large scale in Canada.

The hardness and relative purity of the ore have commended it to consumers, and, with the return of the world to less abnormal conditions, important developments can be anticipated on the Postmasburg Manganese Fields.

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# METAMORPHISM AND HYDROTHERMAL ALTERATION OF THE HOMESTAKE GOLD-BEARING FORMATION.[1]

J. K. GUSTAFSON.

CONTENTS.

Introduction ..... 123
General Geology ..... 126
Major features ..... 126
Pre-Cambrian column ..... 127
Homestake formation ..... 128
Tertiary intrusives ..... 131
Mineralogy of the Homestake Formation ..... 131
Paragenesis ..... 131
Descriptive mineralogy ..... 134
Regional Metamorphism ..... 141
General concepts ..... 141
Formation of cummingtonite ..... 144
Formation of biotite, chlorite, and garnet ..... 147
Nature of solutions ..... 147
Equilibrium ..... 151
Temperature, pressure, time ..... 153
Hydrothermal Metamorphism ..... 155
Distinctive features ..... 155
Spatial relations of hydrothermal minerals ..... 155
Nature of solutions ..... 156
Source of solutions ..... 157
Equilibrium ..... 158
Summary ..... 160

## INTRODUCTION.

THE gold ore bodies of the famous Homestake mine at Lead, South Dakota, are confined to one relatively thin, folded layer of rock in the metamorphosed pre-Cambrian sediments of the northern Black Hills. It constitutes a distinct geologic unit termed

[1] Material abstracted from a Doctor's dissertation, Harvard University, 1930.

the Homestake formation. This important relationship was first recognized in 1923 by Paige,[2] and Hosted and Wright.[3] These great ore bodies, from which over $266,000,000 in gold has been recovered during the past fifty-five years and which in 1931 produced $8,935,307, are local replacements in the Homestake formation where structural and other features favored introduction and deposition of gold and accompanying minerals. The ore is thus made up of minerals derived from the original sedimentary material, recrystallized and profoundly modified, and from elements introduced into the rock with the gold, subsequent to the major changes due to regional metamorphism.

*Statement of Problem.*—This investigation of the Homestake formation was undertaken primarily to distinguish the regional sedimentary constituents, the products of regional metamorphism, and the minerals formed by later hydrothermal processes, and to attain a clearer and more accurate understanding of the development of the rock and ore. In the course of the work a new surface geologic and topographic map of an area 1¾ by 2 miles adjacent to the mine was prepared on a scale of 400 feet to the inch; evidence was established for a clearer mineralogical distinction between the earlier regional metamorphism and the later local hydrothermal metamorphism; the physical and chemical conditions obtaining during both metamorphic periods were considered, and their application to the problem studied, and further proof was obtained of the pre-Cambrian age of ore emplacement.

*Acknowledgments.*—It is a pleasure to acknowledge the aid received in the course of this work. It was financed by the Holden fund of the department of Mineralogy and Petrography of Harvard University and by the Homestake Mining Company. Professor D. H. McLaughlin suggested and sponsored the investigation. He also spent a week with the writer in the mine

[2] Paige, Sidney: The Geology of the Homestake Mine. Econ. Geol., vol. 18, pp. 205–237, 1923. Geology of the Region around Lead, South Dakota, and its Bearing on the Homestake Ore Body. U. S. Geol. Surv. Bull. 756, 1924.

[3] Hosted, J. O., and Wright, L. B.: Geology of the Homestake Ore Bodies and the Lead Area of South Dakota. Eng. and Min. Jour., vol. 115, pp. 793–799, 836–843, 1923.

and on the surface, discussed the problems with him, and helpfully criticized the manuscript. Professor E. S. Larsen gave much encouraging advice during the laboratory studies and the writing of the paper. Mr. Clarence Kravig ably assisted in the field. Greatly appreciated are the many courtesies extended to the writer in Lead by the staff of the Homestake Mining Company. Mr. B. C. Yates, general manager, kindly permitted publication of this paper. Dr. A. B. Yates gave photographic and drafting aid, as well as helpful criticism, and Mr. Arthur Lease provided a number of useful illustrations.

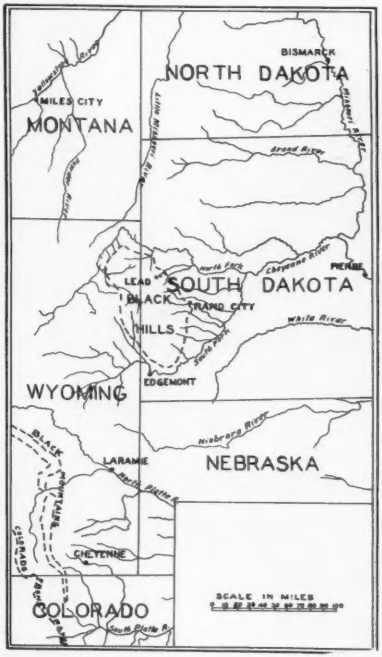



FIG. 1. Key map showing position of Lead in the northern Black Hills.

GENERAL GEOLOGY.

*Major Features.*—The Black Hills dome with its central core of metamorphic and plutonic rocks, the encircling bands of successive Paleozoic and Mesozoic sediments, and the irregular interruptions due to the Tertiary prophyries, are too well known to

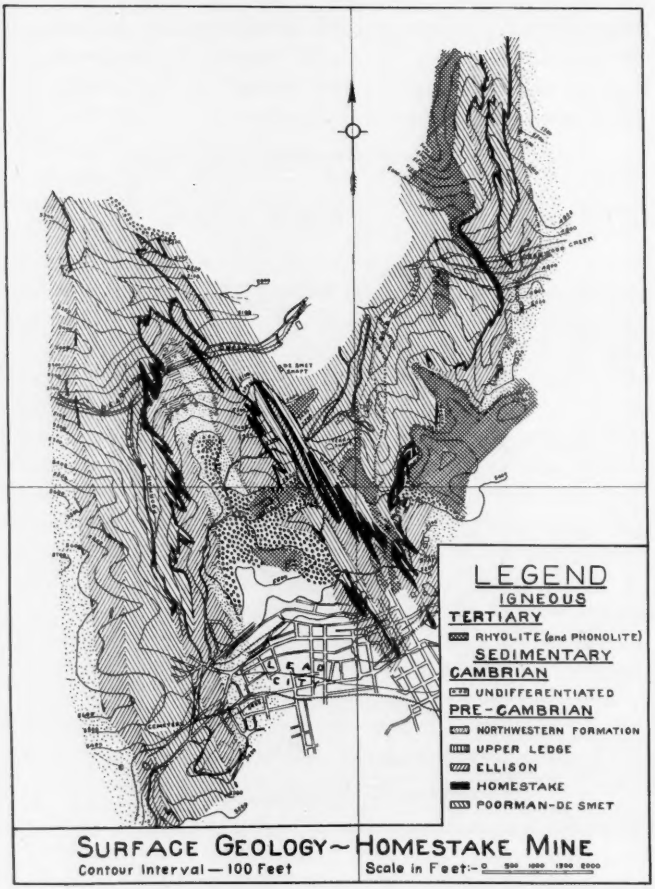



FIG. 2. Surface geology of the Homestake Mine area.

require general description. The area near Lead, with which this paper is primarily concerned, is near the northern limit of exposed pre-Cambrian rocks and includes representatives of all the major classes except the plutonic intrusives.

The larger geologic units of the area are as follows: (1) a thick series of schistose pre-Cambrian sedimentary rocks, crumpled and sheared into tight folds, which plunge to the south and southeast; (2) the conglomerate, sandy, or limy, beds of the Cambrian Deadwood formation capping the tops of hills not occupied by rhyolite sills; (3) Tertiary rhyolite or rhyolite-porphyry sills capping the hills and splitting the Deadwood formation; (4) irregular rhyolite dikes—apparently the feeders for the sills; and (5) the Homestake ore body, a hydrothermal gold-quartz replacement deposit in certain folds of the Homestake formation. Bodies of Tertiary siliceous gold and gold-tungsten ores in the Cambrian dolomites formerly worked in the vicinity of Lead are not shown on the map.

*Pre-Cambrian Column.*—The metamorphosed sedimentary rocks in this region were divided into convenient lithologic groups by Hosted and Wright,[4] who gave them formation names as follows: Poorman formation (oldest), DeSmet formation, Homestake formation, Ellison formation, West Ledge formation, Northwestern formation, Garfield formation, and Pluma formation (youngest). Each formation is an assemblage of altered bedded rocks with certain types sufficiently dominant to make identification possible in areas where exposures are plentiful, even though the same rock types are repeated in many of the formations. The dark colored dioritic intrusives cutting the sedimentary rocks were also recognized by Paige,[5] and by Hosted and Wright[6] and named "amphibolites."

It was part of the writer's object to study these formations in greater detail and to define them more accurately than had hitherto been attempted. The Garfield and Pluma do not outcrop in the area mapped. The West Ledge formation was renamed Upper

[4] *Op. cit.*
[5] *Op. cit.*
[6] *Op. cit.*

Ledge formation to avoid conflict with other local usage of the term West Ledge. The Poorman and DeSmet formations were combined into the Poorman-DeSmet formation, because they are gradational and form a single convenient mapping unit.

Table I gives the formations with important rock types indicated.

Similar formations recur at intervals as far south as Rochford and the Golden West mine on Castle Creek.

*Homestake Formation.*—The economic significance of the Homestake formation and its value as a key horizon in the intricately folded metamorphic rocks have made it the subject of particular study. Though not uniform in character, the rocks that compose it are nevertheless so distinctive and its diagnostic features so well established, that the formation can be mapped with greater accuracy than any other pre-Cambrian unit.

The Homestake formation (Fig. 3) is a laminated aggregate of beds of quartz-cummingtonite-biotite schist, containing locally subordinate garnet, chlorite, and carbonate; of quartz-carbonate schist with subordinate biotite and chlorite; and of chlorite-quartz schist which is commonly garnetiferous. Thin layers of granular quartzite, derived from lenses of quartz sand, reveal the bedding of the formation and clearly show details of the folded structures (Fig. 4). Where most intensely contorted, the quartzite layers may be pulled apart and the material rolled into a series of discontinuous cigar-shaped pods that lie in the plane of bedding and plunge parallel to small adjacent drag folds.

The formation prior to metamorphism was a thin-bedded sediment containing clay, sand, and impure iron-magnesium carbonate layers. The average thickness of the Homestake formation is perhaps 60 feet, although no reliable measurement is possible on account of the thinning and thickening of the beds in the folds.

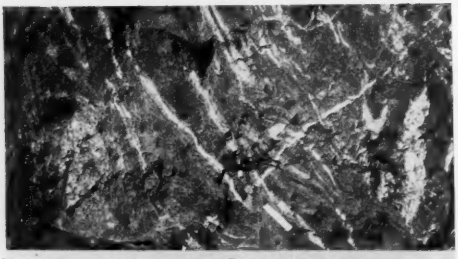
The dull greenish or brownish amphibole, cummingtonite, with characteristic fibrous, radiating texture (Fig. 5) is a useful diagnostic mineral for identifying the formation in the mine, but it is of less help on the surface than the brick-red color of oxidized iron-bearing constituents or the presence of numerous quartz pods

TABLE I.

| | |
|---|---|
| Metamorphosed dioritic intrusives | |
| Amphibolites intrusive into the formations | |
| Northwestern formation | |
| Crinkled, coarse,* garnet-mica schists | d+ |
| Thick, medium, micaceous quartzites | d+ |
| Fine, garnetiferous, chloritic quartz-mica schists | + |
| Thin black quartzites | — |
| Slates | — |
| Upper Ledge formation | |
| Coarse cummingtonite-quartz schist | d+ |
| Medium Mg-Fe carbonate-quartz schist | d+ |
| Thin white quartzite lenses and pods | d+ |
| Fine green, garnet-chlorite schist | — |
| Ellison formation | |
| Fine gray slate | d+ |
| Fine slaty, banded, quartz-mica schist | + |
| Thin black quartzites | d— |
| Fine, massive, quartz-carbonate schist | — |
| Fine, banded, chloritic and garnetiferous schist | — |
| Medium, gray, micaceous quartzites | d— |
| Homestake formation | |
| Coarse, cummingtonite-quartz schist | d+ |
| Medium Mg-Fe carbonate-quartz schist | d+ |
| Thin white quartzite lenses and pods | d+ |
| Fine green garnet-chlorite schist | — |
| Poorman-DeSmet formation | |
| (Upper tenth) | |
| Coarse, garnet-mica schist | d+ |
| Fine, banded, chlorite-garnet-quartz-mica schist | d+ |
| Fine, banded, gray, dolomitic phyllite | d— |
| Medium, Mg-Fe carbonate-quartz schist | — |
| Fine, gray, carbonate-mica schist | — |
| (Lower nine tenths) | |
| Fine, banded, gray, dolomitic phyllite | d+ |
| Fine, banded, carbonate-mica schist | + |
| Coarse, tremolite-quartz-carbonate schist | d— |
| Medium, garnet-mica schist | — |
| Fine, chlorite-garnet-quartz-mica schist | — |
| Coarse, garnet-mica schist | — |

+, abundant; —, less abundant; d, diagnostic.

* The terms "coarse" "medium" or "fine" refer to coarse-, medium-, or fine-grained.



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4

5

FIG. 3. Outcrop of Homestake formation (quartz-sideroplesite-biotite schist) with numerous thin quartzite beds. A small quartz vein extends from upper right to lower left. North side of Deadwood gulch near the open cut.

FIG. 4. Outcrop of cummingtonite schist with folded quartzite layers showing tension cracks. North side of road, several hundred yards east of Rochford.

FIG. 5. Hand specimen and drill core showing radial cummingtonite traversing schistosity. $\frac{5}{8}$ natural size. (Photo by Lease.)

and layers. The fresh rock for the most part is greenish gray. The characteristic cabonate is the iron-magnesium variety sideroplesite. The garnet is impure almandite.

There is considerable variation in mineral composition. For example, cummingtonite is distributed only sparingly throughout the area west of the open cut. Here the rock is chiefly quartz and carbonate with subordinate biotite and chlorite. On the other hand, cummingtonite is plentiful in most occurrences in the mine and along the limb of the Homestake formation extending northeast from the mine; carbonate is correspondingly less abundant, and quartz pods are less conspicuous.

The Homestake and Upper Ledge formations are practically identical lithologically and cannot ordinarily be distinguished in mapping except by stratigraphic position. The upper contact of the Homestake formation is sharp; the lower contact against garnet schists of the Poorman-DeSmet formation is less definite but can usually be mapped with fair accuracy. These adjacent rocks have been studied closely, and are of much interest, but cannot be described in detail here. (See Table I.)

The ore bodies are remarkably confined to certain dominantly anticlinal minor folds belonging to the main anticline. Ore solutions were apparently channeled by these favorable structures as they ascended in the permeable Homestake formation beneath an impermeable roof of Ellison slates.

*Tertiary Intrusives.*—Imbricated rhyolite dikes of Tertiary age cut through the ore bodies in a northeasterly direction. One Tertiary phonolite cuts across approximately normal to the plunge of the folds.

## MINERALOGY OF THE HOMESTAKE FORMATION.[7]

### *Paragenesis.*

The Homestake formation, through recrystallization accompanying and following folding, reached a stage when it consisted of the following minerals listed in order of abundance: (1)

[7] The following discussion holds as well for the Upper Ledge formation as for the Homestake formation, as the two are mineralogically very similar.

quartz and sideroplesite (or cummingtonite), (2) cummingtonite, (3) biotite, (4) chlorite, (5) garnet, (6) graphite or carbonaceous material in some other form, and (7) sericite (negligible). Later the rock was locally invaded by hydrothermal solutions, which formed quartz veins and impregnated the walls with arsenopyrite, pyrrhotite, pyrite, ankerite, chlorite, other less abundant minerals, and gold.

These general changes were recognized by Paige,[8] Hosted and Wright,[9] Connolly,[10] Gibson,[11] and McLaughlin,[12] although a clear mineralogical distinction was not made between the regional metamorphism and the local hydrothermal metamorphism. Rock carbonate and chlorite were not distinguished from hydrothermal carbonate and chlorite, and all the silicates were assigned by Connolly to the ore-forming stage.

Table II summarizes the essential paragenetic changes.

The evidence for this sequence is as follows: Garnet grains are sheared and rotated, and therefore formed before folding ceased. Delicate radiating fibers of cummingtonite, which formed from a reaction between sideroplesite and quartz, cut across bedding and schistosity and are neither bent nor broken; they are, therefore, post-folding in age. Biotite replaces garnet and cummingtonite; chlorite replaces garnet, cummingtonite, and biotite. Rarely biotite and chlorite grains appear to have been partly rotated by movements on schist planes. Hence, small amounts of these minerals may have existed during late folding, or some slipping on bedding planes, sufficient to deform and orient biotite and chlorite but insufficient to affect cummingtonite, may have continued into the "post-folding" stage. Quartz occurs as polygonal grains (original sand grains slightly altered as

[8] *Op. cit.*

[9] *Op. cit.*

[10] Connolly, Joseph: Tertiary mineralization of the Northern Black Hills. So. Dakota School of Mines, Bull. 15, 1927.

Connolly, Joseph, and O'Harra, Cleophas C.: The Mineral Wealth of the Black Hills. So. Dakota School of Mines, Bull. 16, 1929.

[11] Gibson, Russell: Discussion of the Criteria of Deep-Seated Gold-Quartz Deposits. Doctor's Dissertation, Harvard University, 1928.

[12] McLaughlin, D. H.: Private reports to the Homestake Mining Company.

TABLE II.

| | Mineral | | Period | | | | |
|---|---|---|---|---|---|---|---|
| | | | Pre-Folding | Folding | | Post-Folding | |
| | | | | Early | Late | Regional | Local |
| Early | Carbonaceous matter | Contemporaneous | X | x | x | x | x |
| | Sideroplesite | | X | x | x | x | x |
| | Quartz | | X | x | x | x | x |
| | Clay minerals (or) mica, chlorite | | X | (x?) (X?) | (x?) | | |
| | Garnet | Overlapping | | | X | x | x |
| | Cummingtonite | | | | | X | x |
| | Biotite | | | | | X | x |
| | Chlorite | | | | | X | x |
| Late | Quartz | Overlapping | | | | | X |
| | Ankerite | | | | | | X |
| | Asp, po, py, Au | | | | | | X |
| | Chlorite, Au (?) | | | | | | X |

X....new mineral.
x....residual mineral.

to shape) which are more or less replaced by silicates, and as irregular recrystallized grains some of which replace silicates. Sideroplesite was obviously an original mineral, but recrystallized sideroplesite replaces silicates. Although cummingtonite, biotite, and chlorite formed after the cessation of virtually all shearing movements, they formed during the continuation of directed stress, since biotite and chlorite cleavages in rock containing little cummingtonite are oriented parallel to one another and to bedding. Where cummingtonite is abundant, however, the platy minerals are more or less randomly oriented. Cummingtonite was insensitive to the stress differences, and its interlocking fibers evidently dispersed stresses which otherwise would have caused biotite and chlorite to be recrystallized with parallel orientation.

Even later hydrothermal chlorite replacing unoriented cummingtonite in sufficient amount, possesses parallel orientation.

The order of deposition of ore minerals[13] inferred from replacement textures is: (1) arsenopyrite, (2) pyrrhotite, overlapping with (3) pyrite, (4) chalcopyrite, sphalerite, magnetite, galena, (5) gold. Minerals in group (4) are unimportant.

Some precipitation of quartz and ankerite continued after that of sulphides, although most of the quartz and ankerite are older than the sulphides or in part contemporaneous with them. Most of the ankerite probably precipitated contemporaneously with quartz (and albite), although some is younger. Chlorite generally appears younger than ore minerals and older than gold, but the evidence is not compelling.

## *Descriptive Mineralogy.*[14]

*Quartz.*—Weathered quartzite layers and pods in the Homestake formation ordinarily reveal small, rounded, sandy grains of quartz which in thin section prove to be imperfect polygonal sand grains, but slightly altered from their original shape (Fig. 6). In the more highly deformed pods, the polygonal grains have been for the most part recrystallized to larger irregular grains with sutured boundaries.

The polygonal grains in some instances tend towards dimensional orientation; long diameter parallel to, or making an acute angle with, bedding (schistosity), and the crystallographic orientation: $\varepsilon'$ (c-axis) parallel to or making an acute angle with bedding (schistosity). The irregular grains in some cases show the orientation: $\varepsilon'$ making an angle of 45–90 degrees to bedding and schistosity, with the long diameter generally parallel to $\varepsilon'$ ("Trener rule"). These grains commonly exhibit undulatory extinction parallel to $\varepsilon'$.

The inference is that the polygonal grains were oriented by mechanical rotation and the irregular grains by crystallization

[13] Gibson, Russell: *Op. cit.*

[14] Descriptions of the ore minerals are omitted from this discussion, because they have been fully described by Connolly, Gibson, and Paige in the references cited.

under differential stresses, although Sander,[15] Schmidt,[16] and their collaborators regard the Trener habit as the result of purely mechanical processes.

Both these types of grains occur in thin laminae and scattered through the matrix of other beds in the Homestake formation, as do interstitial and cataclastic quartz grains showing no crystallographic orientation.

Hydrothermal quartz is commonly difficult to distinguish in thin section from the earlier recrystallized quartz. The texture is much the same, but the grain size is apt to be larger. Many grains possess the same undulatory extinction, but too few slides were studied to be certain that any rule of dimensional or crystallographic orientation can be applied.

*Carbonate.*—The recognition of ankerite as the hydrothermal carbonate and sideroplesite as the rock carbonate was reached by comparing the indices of refraction of material from carefully

TABLE III.

| Mineral | | Number of Tests | | | |
|---|---|---|---|---|---|
| | | From Veins | | From Body of Rock | |
| | | Quartz (Large) | Carbonate Chlorite | Mineralized Rock (Sulphides); Ore | Unmineralized Rock; Barren |
| Ankerite..... | 1.705–1.733 | 8 | 5 | 9 | 1[a] |
| Sideroplesite..... | 1.818–1.847 | 0 | 3[b] | 4[c] | 15 |

[a] Texture and presence of hydrothermal albite suggests hydrothermal carbonate.
[b] Small veinlets 1 mm. thick, believed to be unrelated to ore period, rare.
[c] Texture suggests residual rock carbonate.

chosen samples of "mineralized" and "unmineralized" rock (Table III). Results were checked repeatedly by textures and mineral associations revealed in thin section.

[15] Sander, Bruno: Über Zusammenhänge zwischen Teilbewegung und Gefüge in Gesteinen. Tschermak's Min. und Pet. Mitt., vol. 30, pp. 281–314, 1911.

Sander, Bruno (with Schmidegg, Oskar): Zur petrographischtektonischen Analyse. Jahrb. der Geol. Bundesanstalt, LXXVI, T. III, pp. 323–406, 1926.

[16] Schmidt, Walter: Gefügesymetric und Tektonik. Jahrb. der Geol. Bundesanstalt, LXXVI, T., III, pp. 407–430, 1926.

Grubenmann, U. and Niggli, P.: Der Gesteinsmetamorphose, p. 415. I. Allgemeiner Teil, Gebrüder Borntraeger, Berlin, 1924.

In thin section hydrothermal carbonate can commonly be told from rock carbonate by its mineral associations, larger grain size (up to several cm.), more irregular grain shape, and lower relief. Most ankerite grains are untwinned, but some show twinning on the negative rhombohedron. Small veinlets of ankerite with or without chlorite also occur. Most sideroplesite occurs as ovaloid grains (.03 — .04 ± mm. long) in fairly pure carbonate laminae and as more ragged grains (.2 — 4 mm. in diameter) where other minerals are plentiful. Occasional isolated porphyroblasts of the same size as the larger grains, some of them rotated, appear in quartzite layers. Long diameters and growth lines indicate greatest growth parallel to bedding (schistosity).

Fourteen measurements of sideroplesite yielded values for $\omega$ ranging between 1.820 ± .01 and 1.847 ± .01, with the majority close to 1.835 ± .01. Twenty-four measurements of $\omega$ of ankerite gave values between 1.705 ± .003 and 1.733 ± .03. The following analyses, with one exception, were published by Sharwood and Paige as indicated below. The refractive indices were calculated [17] by the writer.

| | 52[a] | 53[a] | 51[a] | 1095[b] | 1[c] | 2[c] | 3[c] | 4[c] |
|---|---|---|---|---|---|---|---|---|
| $CaCO_3$ | 0 | 1.19 | 49.12 | 46.83 | 0 | 5.5 | .07 | 0 |
| $MgCO_3$ | 22.5 | 6.93 | 18.08 | 15.32 | 5.4 | 9.6 | 2.5 | 5.2 |
| $FeCO_3$ | 77.5 | 90.30 | 32.47 | 33.75 | 11.6 | 4.7 | 11.6 | 13.4 |
| $MnCO_3$ | Tr. | 1.67 | 0.11 | 4.10 | N.D. | N.D. | N.D. | N.D. |
| Impurities | 8.6 | .64 | N.D. | N.D. | 16.0 | 28.3 | 0 | 11.0 |
| $\omega$ | 1.826 | 1.866 | 1.736 | 1.744 | 1.823 | 1.729 | 1.843 | 1.826 |

[a] Analysis by W. J. Sharwood, (Analyses of some Rocks and Minerals from the Homestake Mine, Lead, South Dakota. ECON. GEOL., vol. 6, pp. 729–789, 1911).

[b] Analysis by Sharwood, furnished to writer by Dr. Russell Gibson; carbonate in vein quartz.

[c] Analysis published by Sidney Paige, (U. S. Geol. Surv. Bull. 765, p. 18, 1924); impurity is $Fe_2O_3$ (as limonite).

Nos. 52, 1, 3, and 4 are fairly typical of the rock carbonate. No. 53 (siderite) is doubtless a rock carbonate but richer in iron

[17] Ford, W. E.: Studies in the Calcite Group. Trans. Conn. Acad. Arts and Sci., vol. 22, pp. 211–248, 1917.

than usual. Nos. 51, 1095, and 2 are typical of hydrothermal ankerite.

*Garnet.*—Garnet occurs as euhedral grains .4 mm. to 6 mm. in diameter between folia of biotite and chlorite. The fresh mineral is pink, but chlorite imparts a greenish cast to altered grains.

Sharwood[18] gives a chemical analysis of garnet from chlorite schist from the Caledonia raise, 800-foot level.

Four index of refraction measurements of garnet from the Homestake formation yielded values between 1.811 ± .01 and 1.814 ± .01. According to curves by Ford,[19] the theoretical refractive index of a garnet having the composition of the one analyzed by Sharwood (approximately 77 per cent. almandite, 13 per cent. pyrope, 10 per cent. spessartite) is 1.811. The garnet, therefore, can be regarded as typical of the formation.

*Cummingtonite.*—Cummingtonite occurs as brownish to greenish tufts of radiating fibers that may measure several centimeters in length, although the majority do not exceed 5 mm. Table IV

TABLE IV.

| | Lead, S. D.[a] | Mt. Humbold[b] | Cummington, Mass.[c] |
|---|---|---|---|
| $SiO_2$ | 52.77 | 49.84 | 51.09 |
| $Al_2O_3$ | 1.55 | .62 | .95 |
| $Fe_2O_3$ | — | .44 | — |
| FeO | 34.02 | 33.70 | 32.07 |
| MnO | .45 | .57 | 1.50 |
| MgO | 8.16 | 6.23 | 10.29 |
| CaO | .95 | 1.45 | trace |
| $Na_2O$ | .40 | 1.05 | .75 |
| $K_2O$ | — | .12 | trace |
| $H_2O$ | 1.70 | 5.98 | 3.04 |
| Total | 100.00 | 100.00 | 99.60 |
| Sp. G. | 3.37 | — | 3.42 |

[a] Sharwood, W. J., analysis No. 44b. (*Op. cit.*, p. 747.)

[b] Richarz; quoted by W. Kunitz. (Neuen Jahrb. für Min., Beil. Bd., LX, Abt. A, p. 189, 1929.)

[c] Smith and Brush; quoted by Sharwood (*Idem.*).

[18] *Op. cit.*, p. 752.

[19] Ford, W. E.: A Study of the Relations Existing between the Chemical, Optical, and other Physical Properties of the Members of the Garnet Group. Amer. Jour. Sci. (4), vol. XL, fig. 7, p. 44, 1915.

is an analysis of Homestake cummingtonite compared with analyses of similar amphiboles from other localities.

Twenty-one measurements of refractive indices of Homestake cummingtonite fell within the following limits:

$$\gamma = 1.683 - 1.710 \pm .003$$
$$\beta = 1.669 - 1.692 \pm .003$$
$$\alpha = 1.654 - 1.673 \pm .003$$

The averages of fourteen measurements occupying the flat region of a curve on which these indices were plotted are:

$$\gamma = 1.698 \pm .003; \beta = 1.682 \pm .003; \alpha = 1.665 \pm .003.$$

These appear to be about right for the composition given by Sharwood. Optical data for the three amphiboles are given in Table V.

TABLE V.

| Optics | Mt. Humbold | Lead, S. D.[a] | Cummington, Mass.[a,b] |
|---|---|---|---|
| $\gamma$ | 1.700 | 1.698 ± .003 | 1.689 ± .003 |
| $\beta$ | 1.684 | 1.682 ± .003 | 1.673 ± .003 |
| $\alpha$ | 1.666 | 1.665 ± .003 | 1.656 ± .003 |
| Sign | (—) | (—) | (—) |
| 2V | 85° – 86° | 82°[c] 88° 16'[d] | Large |
| ZC | 14° – 15° | 17° – 18° | 18° |
| | Y = b | Y = b | Y = b |

[a] New optical data.
[b] Mineral from Brush Collection, Yale University.
[c] Measured with Federow stage.
[d] Calculated from indices of refraction.

The fresh Homestake mineral is colorless to faint brown and non-pleochroic in thin section. In a few thin sections cummingtonite attacked by chlorite, magnetite, carbonate, and sulphides is distinctly pleochroic: Z = bluish green, Y = X = brown; Absorption, weak; Z > Y = X. The fibers of cummingtonite are repeatedly twinned on (100). Twin individuals average .2 mm. in thickness.

Cummingtonite was recrystallized for a few inches around some quartz masses into a silky asbestiform substance. Fibers of

this material in some cases are four to six inches long. Chemical analysis [20] and optical data prove this to be cummingtonite. In one instance, however, slightly lower indices were measured, and the mineral was too finely fibrous to tell whether it was orthorhombic or monoclinic.

*Biotite.*—Biotite occurs as brown platy grains whose long and mean diameters average around .13 mm. in length. Parallel orientation is common. Index of refraction measurements show that the composition of the mineral is not uniform. Twenty-eight measurements of $\gamma = \beta$ ranged between $1.672 \pm .003$ and $1.645 \pm .003$. The first is an aberrantly high value and was obtained on zoned material giving values between $1.672 \pm .003$ and $1.655 \pm .003$. The rest fell on a nearly straight line between $1.665 \pm .003$ and $1.645 \pm .003$. Four measurements of $\alpha$ indicated a birefringence of between .053 and .059.

An analysis of unusually large biotite plates is given by Sharwood.[21]

All the biotite is optically (—) and sensibly uniaxial. The acute bisectrix (X) is practically normal to the base. Dispersion, distinct $\rho < \nu$. Pleochroism ordinarily X = pale straw yellow to greenish yellow; Y = Z = dark brown to dark greenish brown, nearly opaque. Absorption $X < Y = Z$.

Some green biotite occurs; and there is reason to regard this as a hydrothermal product intermediate in the change from biotite to chlorite, which resulted when ore solutions penetrated country rock long distances from their avenue of entrance.

Insignificant amounts of brown biotite appear to have been introduced or recrystallized by hydrothermal solutions. Such biotite is closely confined to sulphides in rock containing little chlorite.

*Chlorite.*—Most of the chlorite schist of the formation is ore-bearing or is close to ore and received its chlorite from ore solutions. Repeated comparisons of the chlorite from "unmineralized" and "mineralized" rock (Table VI) show that rock

[20] Sharwood, W. J.: *Op. cit.*, analysis No. 45, p. 747.

[21] Sharwood, W. J.: *Op. cit.*, analysis No. 45, p. 753.

chlorite and hydrothermal chlorite are similar, but they can ordinarily be distinguished in thin section or in hand specimen.

Rock silicates, especially biotite, were readily attacked by chlorite. Some hydrothermal chlorite is intergrown with quartz and ankerite in veins.

TABLE VI.

| Mineral | $\omega$ | Number of Tests | | |
|---|---|---|---|---|
| | | At or Near Quartz Veins | Mineralized Rock (Sulphides); Ore | Unmineralized Rock; Barren |
| Chlorite | 1.626 – 1.640 | 4 | 10 | 0 |
| Daphnite (approximately) | 1.641 – 1.643 | 1 | 3 | 2[a] |
| | 1.644 – 1.647 | 0 | 6[b] | 7 |
| | 1.648 – 1.657 | 0 | 0 | 6 |

[a] Resembles hydrothermal chlorite in thin section.

[b] Three specimens are believed to be rock chlorite; the others are probably hydrothermal.

Seventeen specimens judged to be rock chlorite gave values for $\gamma = \beta$ between $1.642 \pm .003$ and $1.657 \pm .003$. The majority were between $1.642 \pm .003$ and $1.648 \pm 003$. The birefringence is between .003 and .006. The higher index material has the greater birefringence. The value of $\gamma = \beta$ of hydrothermal chlorite ranges between $1.626 \pm .003$ and $1.642 \pm .003$, according to twenty measurements. The majority of values are between $1.626 \pm .003$ and $1.640 \pm .003$. The birefringence is between .002 and .004.

Both rock and hydrothermal chlorite are practically uniaxial and are optically (—). X is essentially normal to the base. The pleochroism and absorption are strong with: X = light greenish, straw yellow, Y = Z = dark green; Y = Z > X. The greenish yellow and grayish blue maximum interference colors of rock chlorite help to distinguish it from typical hydrothermal chlorite, which commonly exhibits abnormal deep blue and reddish purple maximum interference colors.

Several analyses of chlorites are given by Sharwood.[22] His

[22] *Op. cit.*, p. 745.

No. 40*a* (and 40*b*) and No. 41*a* (and 41*b*) are almost surely hydrothermal chlorite, since they occurred in ore with arsenopyrite. His No. 42 is "in minute scales or plates . . . from a mass occurring with pyrrhotite and magnesian siderite."[23] This is probably also hydrothermal but of the brighter green and higher index variety that occurs away from quartz veins and ore, and whose optical properties approximate those of most rock chlorite. Its associations, pyrrhotite and sideroplesite, suggest this variety.

*Other Minerals.*—Original carbonaceous material, now probably graphite, is seen in most thin sections as thin, wispy films parallel to bedding, which were incorporated by some minerals and rejected by others during recrystallization. Sericite, a rock mineral, and albite, tourmaline, and apatite, hydrothermal minerals, are too infrequently encountered to warrant discussion.

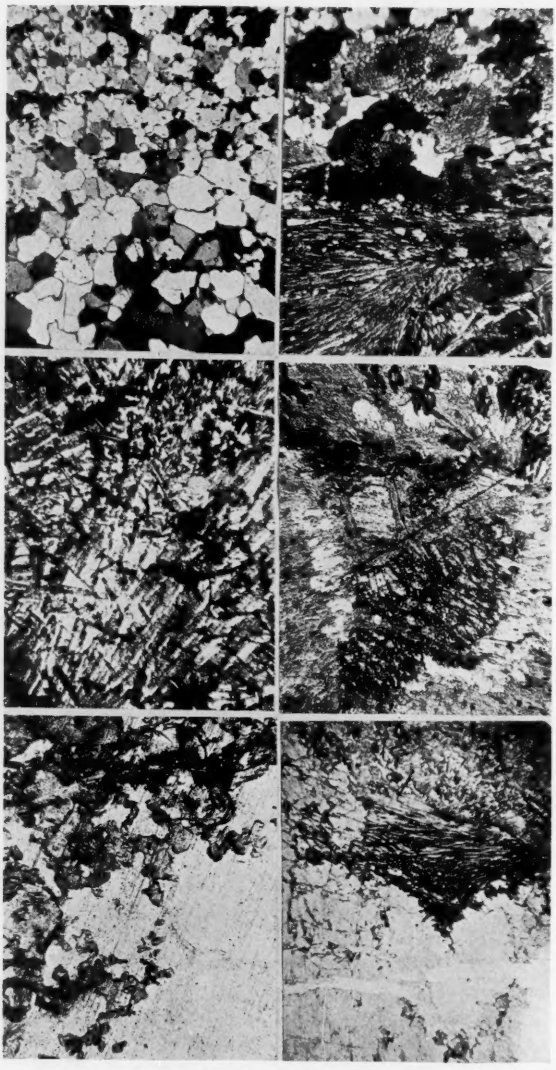
## REGIONAL METAMORPHISM.

*General Concepts.*—The principle that chemical systems tend to become adjusted to their external physical environment was established as a basis for the study of metamorphism by the early works of F. Becke, U. Grubenmann, and C. R. Van Hise. These workers recognized depth zones, each characterized by sets of minerals and rocks.

Later expositions of metamorphic changes set forth chiefly by V. M. Goldschmidt, P. Eskola, U. Grubenmann, and P. Niggli, have shown that temperature and pressure acting upon material of given chemical composition determine the mineral assemblage where equilibrium is reached regardless of the mode of crystallization. Rather perfect states of equilibrium are shown to have existed in some metamorphic areas, and the conception of mineral facies has been introduced. Co-existent with the idea of mineral facies is the idea of metamorphic provinces and metamorphic rock series.[24]

[23] *Idem.*, p. 744.

[24] For a general review of this subject, consult: Grubenmann, U. and Niggli, P.: Die Gesteinsmetamorphose, I. Algemeiner Teil, pp. 478–498, Gebrüder Borntraeger, Berlin, 1924; Erdmannsdorfer, O. H.: Grundlagen der Petrographie, pp. 261–275, F. Enke, Stuttgart, 1924; Tyrrell, G. W.: The Principles of Petrology, pp. 251–312, E. P. Dutton & Co., New York, 1926.



6 7

8 9

10 11

Two general methods of study have been pursued by investigators of metamorphism. One has been to study the effect of a range of external conditions (of temperature and pressure) upon a group of rocks of essentially the same bulk composition, *i.e.* an iso-chemical rock series. The other has been to study the effects of the same external conditions upon rocks of differing chemical composition, *i.e.* an iso-physical rock series. An example of the first type is Eskola's investigation in southwestern Finland of a series of metamorphic rocks with the bulk composition of a gabbro.[25] An example of the second type is included in V. M. Goldschmidt's study in the Kristiania region, Norway, of the metamorphic derivatives of a series of sediments ranging from clay slates to marls in contact zones, although both points of view are considered in this exposition.[26]

As a whole, the rocks of the Lead area are practically an iso-physical series, whereas the Homestake formation itself (or to-

FIG. 6. Thin section showing polygonal quartz grains in quartzite pod from the Homestake formation. Note gradation in grain size across bedding. Crossed nicols; × 35.

FIG. 7. Thin section of Homestake formation showing cummingtonite, sideroplesite, and polygonal quartz together. Crossed nicols; × 28.

FIG. 8. Thin section of cummingtonite-quartz-biotite (-sideroplesite) schist of the Homestake formation. Small, dark, randomly oriented plates of biotite are seen cutting across cummingtonite fibers. × 26.

FIG. 9. Thin section showing sheared and rotated garnet grain in somewhat mineralized cummingtonite-chlorite-quartz schist of the Homestake formation. Light area around garnet is composed of infiltrated quartz. Dark patches above the garnet grain are cummingtonite fibers partially replaced by finely granular siderite (rare). × 24.

FIG. 10. Thin section of a quartz vein from rich ore showing intergrown hydrothermal quartz and chlorite. Arsenopyrite occurred in the schist around the margins of this vein. × 30.

FIG. 11. Thin section showing replacement of cummingtonite-quartz schist by a single large grain of hydrothermal ankerite. × 26.

[25] Eskola, Pentti: The Mineral Facies of Rocks. Norsk Geol. Tidskrift, vol. VI, 1920.

[26] Goldschmidt, V. M.: Geologische-petrographische Studien in Hochgebirge des Südlichen Norwegens. Die Kontaktmetamorphose im Kristianagebiet. Vidensk, Skr. I, Mat. naturv. Kl. No. kk, 1911.

gether with the Upper Ledge formation) is practically an isochemical series.

The ideal conception of mineral facies [27] and rock series [28] rests upon certain fundamental assumptions that must be borne in mind if they are to be applied to any area. Among these assumptions are:

(1) That there was a certain uniformity of physical conditions.
(2) That equilibrium throughout the rock mass was reached.
(3) That studies of certain kinds of rocks, say of gabbro composition, in one area are directly comparable to studies of different kinds of rock, say of granite composition, in other areas.

The evidence in the Lead area pertaining to these questions will be set forth in the following pages.

*Formation of Cummingtonite.*—The interaction between sideroplesite and quartz to give cummingtonite is analogous to the simpler and more familiar reaction whereby wollastonite is formed from calcite and quartz,—

$$RCO_3 + SiO_2 \rightleftharpoons RSiO_3 + CO_2.$$

The chief factors determining the reaction in nature are temperature, pressure, and degree of mixing of the solid constituents. Increased temperature favors the formation of the silicate. In a closed system the reaction would proceed to the right only when the pressure of $CO_2$ exceeded the external pressure, but in nature the gas phase can slowly escape and thus keep the partial pressure of $CO_2$ low and permit the silicate to form. The rate of reaction may depend largely on the rate of escape of $CO_2$.

Discontinuous carbonate layers interbedded with cummingtonite rock, both containing thin quartzite layers, are found in the Caledonia and Incline stopes and elsewhere. Carbonate rock with sedimentary quartz pods and layers, almost entirely free of cummingtonite, is the characteristic rock of the Homestake formation in the country immediately west of the Homestake mine workings.

[27] Eskola. *Op. cit.*, p. 146.

[28] See quotation from Brögger. Grubenmann, U., Niggli, P.: *Op. cit.*, p. 481.

The following relationships between cummingtonite and rock structure were noted in the mine area:

(1) The most abundant and best developed cummingtonite occurs in the extreme noses of anticlinal folds south of ore. Notable examples are the southern tips of Number Four and Pierce Ledges, and the sheared-off "pod" on the east side of Number Five Ledge. Good cummingtonite occurs consistently in all anticlinal noses.
(2) Synclinal folds (except the Caledonia) show no unusual cummingtonite and generally less cummingtonite than anticlinal folds. The Caledonia is a complex synclinal fold doubled back on itself, so that parts of it are anticlinal structurally.
(3) The large synclinal fold west of the open cut contains very little and only poorly developed cummingtonite.
(4) Large and well formed cummingtonite growths are found in the structurally anticlinal parts of the Caledonia syncline.

The stratigraphic position of the coarse cummingtonite, it will be noted, is usually at or near the Ellison-Homestake contact. Ordinarily in the mine area, less abundant and more poorly developed cummingtonite is encountered as one works across the strike from the Ellison to the Poorman-DeSmet contact, although the transition may be interrupted by carbonate or biotite-garnet beds. There may have been a sedimentary layer near the top of the formation which became bunched in anticlinal crests. The amount of cummingtonite diminishes along the strike from east to west until the main large syncline is reached. Here the drop-off in cummingtonite is abrupt and not adequately explained by sedimentary differences.

Thin sections of rock containing abundant cummingtonite almost invariably show fine-grained original quartz. The amount of quartz indicates silica in excess of that required to build cummingtonite. Many slides show quartz, cummingtonite, and siderophlesite together. No cummingtonite was observed (megascopically) in carbonate rock at the contacts of sedimentary quartz layers. The formation of cummingtonite appears to have been favored in carbonate-quartz rock with fine quartz grains in a carbonate matrix, but even in such material cummingtonite is not everywhere present. Its absence indicates clearly that the condi-

tions of temperature, the presence of water, the possibility of escape of carbon dioxide, or other physical factors necessary for its formation, did not exist uniformly over the region.

There is no evidence from rock structures or textures to explain why the escape of carbon dioxide should have been inhibited in some beds and permitted in others, nor why the ground west of the mine should have been impermeable to gas, whereas the formation elsewhere contains cummingtonite throughout many miles of outcrop. Differences in pressure and temperature due to variation in the degree of folding from place to place were suggested by McLaughlin [29] to explain the irregular distribution of cummingtonite. The absence of cummingtonite probably denotes failure to reach sufficient temperature rather than the attainment of excessive heat. Because it is difficult to consider the temperature resulting from shearing as greater in anticlinal crests than in synclinal troughs or on the flanks of folds, the writer believes some mechanism such as moving water must be hypothecated as the carrier of heat. Folding having ceased, differences in pressure were probably slight at the time cummingtonite formed, although slight differences in pressure may greatly affect such reactions involving a gas phase. They would also be important in distributing water. It is thought that actively moving hot solutions, deriving their heat from a source other than the enclosing rock and ascending because of greater rock pressure at depth, were impounded under the impermeable Ellison slates and channeled by anticlinal folds, where they facilitated the reaction between carbonate and quartz.

Except for a few, thin, scattered, and discontinuous tremolite-actinolite beds, the great thickness of metamorphosed dolomites and marbles of the Poorman-DeSmet formation in the area is devoid of amphibole. Limy quartzite beds in the Ellison formation also contain no amphibole. The distribution of an amphibole in the Poorman-DeSmet formation thus offers the same problem as in the Homestake formation. Since the carbonate rocks of the lower formations generally contain but little quartz,

[29] McLaughlin, D. H., Personal communication.

the possibility of reaction between quartz and carbonate was greatly lessened. The tremolite- actinolite series probably crystallizes at a higher temperature than the cummingtonite-grunerite series. It is likely that temperatures sufficiently high for tremolite-actinolite formation were local and that they persisted only long enough to produce a little of the mineral in the most favorable places. Possibly only locally was there sufficient water as a catalyst to make the building of tremolite-actinolite possible.

*Formation of Biotite, Chlorite, and Garnet.*—The formation of biotite and chlorite sheds little light on the problem. Wherever cummingtonite is present, biotite and chlorite are younger than the amphibole. If, however, there existed no earlier mica or other alumina-bearing mineral, it is difficult to explain how $Al_2O_3$ and $K_2O$ were held prior to the appearance of the present generation of biotite and chlorite. Garnet grains contain no $K_2O$ and are too few to have furnished all the $Al_2O_3$. Either during and following the formation of cummingtonite, earlier biotite and chlorite recrystallized, or the $K_2O$ and $Al_2O_3$ were held in original clay minerals until late in metamorphic history. Most of the $K_2O$ rejected during the replacement of biotite by chlorite apparently escaped from the system. Not enough sericite or muscovite is present to accommodate it.

*Nature of Solutions.*—From field observations the formation of cummingtonite appears to have been more sensitive to temperature, pressure, and original rock character than that of any other mineral. Cummingtonite is therefore a critical indicator of metamorphic conditions.[30] It has been shown that the mineral is not everywhere present where rock composition would permit. It is however, present, in the eastern limb of the main anticline, in the mine folds, and in the limb of Homestake formation (or almost identical rock) which outcrops between Lead and Rochford and extends farther south to include the King of the West and Golden West properties. Thus, the development of cumming-

[30] Eskola states: "The reactions between the lime-magnesia carbonates and silica are in fact the most sensitive indicators of variations in the pressure and temperature in the rocks that we know." (The Mineral Facies of Rocks, Norsk Geol. Tidskrift, vol. VI, 1920, p. 165.)

tonite is a widespread phenomenon dependent upon fairly uniform temperature and pressure conditions and upon fairly constant chemical and physical characteristics of the formation. Considering the whole area and these data alone, the solutions producing recrystallization might well have been ubiquitous, quasi-static, indigenous to the enclosing rock—possibly dependent upon it for heat, and certainly for chemical composition.

Here (as with the distinction between joints and faults) the determination of movement depends upon the scale in mind. Solutions regarded as static throughout the whole area represented by outcrops of cummingtonite schist might be regarded as having moved when the vicinity of the mine alone is considered.

It is to be expected that constituent minerals will show concomitant variations of composition within a closed system where total composition is constant and the new minerals form entirely at the expense of the old. Conversely, it is to be expected that the composition of the younger minerals will be less dependent on the composition of the older minerals in an open system where the composition veers toward that which will be in equilibrium with the solutions.

In lieu of chemical analysis, indices of refraction of minerals from the same hand specimen have been plotted against indices of refraction of minerals from other hand specimens. (Fig. 12). Index values show the *relative* range in composition.[31]

In figure 12 are plotted from left to right a number of values for $\omega$ of carbonate, n of garnet, $\beta$ of cummingtonite, $\omega$ of biotite, $\omega$ of chlorite, in order of decreasing $\omega$ of biotite. With decreasing values for $\omega$ of brown biotite there is a fairly regular decrease of $\beta$ of cummingtonite and $\omega$ of rock chlorite. Hydrothermal chlorite does not fit the curves, and green biotite is erratic. Hydrothermal carbonate appears to show a slight compositional trend like that of cummingtonite, biotite, and rock chlorite, but the data are few. Several humps in the chlorite curve occur, chief of which is that produced by specimen 19214. Less noticeable peaks occur opposite 19210 and 19266. The complementary

[31] Larsen, Esper S.: The Microscopic Determination of the Non-opaque Minerals, pp. 30–32, U. S. Geol. Surv. Bull. 679, 1931.

peak in the cummingtonite curve is noteworthy. This may mean that chlorite is more dependent upon cummingtonite than upon biotite for index-controlling constituents (chiefly iron), or that a higher index biotite once existed, became unstable, and was destroyed.

Too little is known of micas and chlorites to make indices of refraction mean much with regard to actual composition, although they have value in comparisons. The fact that both mineral

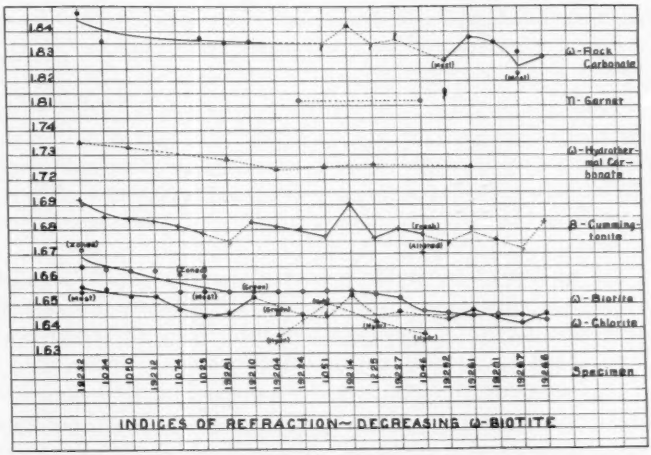



FIG. 12.

groups contain ferric and ferrous iron is complicating, since the specific refractive effect of $Fe_2O_3$ (.308 — .36) is nearly twice that of FeO (.187).[32] Ferric iron therefore increases the index of refraction nearly twice as much as an equal amount of ferrous iron.

These curves suggest that some approach to a closed system was made during regional metamorphism.

Judging from numerous index of refraction measurements, the composition of the original rock carbonate of the Homestake

[32] Larsen, E. S.: *Op. cit.*, p. 31.

formation is fairly uniform in the area. Moreover, ω of unused carbonate in cummingtonite-bearing rock is the same as ω of carbonate in rock containing no cummingtonite. This rather surprising fact means that the amphibole left no residual carbonate of different composition from the original, as might be expected from the break-up of the solid solution $FeCO_3$–$MgCO_3$. The extraction of one component at a faster rate would produce progressive enrichment of the other.

A check was made by comparing weight percentages of the oxides and molecular percentages for Mg and Fe″ from analyses of typical cummingtonite and carbonate.[33]

| | Sideroplesite | | Cummingtonite | |
|---|---|---|---|---|
| | Mol | Wt. % | Mol | Wt. % |
| FeO | 66.9 | 48.06 | 47.35 | 34.02 |
| MgO | 26.68 | 10.76 | 20.23 | 8.16 |
| FeO/MgO | 2.5 | 4.46 | 2.3 | 4.17 |

The difference between the two ratios is well within the limit of error.[34] If the discrepancy is significant, it indicates that during the crystallization of cummingtonite there was progressive, but slight, enrichment of magnesia in the remaining carbonate.

The foregoing indicates a close dependence of cummingtonite composition upon carbonate composition that disfavors the idea that actively moving solutions continually adding new material were responsible for the cummingtonite. The FeO/MgO ratio for chlorite is 2.2.

It is seen that a chemically closed system was approached during metamorphism. It appears to have been closed except for (1) the escape of carbon dioxide attending the formation of cummingtonite, and (2) the escape of potash attending the development of chlorite from biotite—a minor loss chemically. Carbon dioxide did not require solutions for transportation. Solutions, however, doubtless carried potash out of the system.

[33] Analyses Nos. 44b (Table IV) and 52, p. 136.

[34] The error may be large in that both carbonate and cummingtonite have a range of composition, indices of analysed material are not available, and the cummingtonite and carbonate here compared did not occur together.

An important consideration is that a chemically closed system need not be a physically closed system. Water may be able to move with some freedom and yet transport out of the system only insignificant amounts of material, provided it is continually in equilibrium with its immediate environment. Moving solutions conceivably can (1) distribute heat, (2) catalyze reactions, and (3) introduce and carry away material. This study has led to the conclusion that these rocks were affected during metamorphism by water solutions capable of considerable movement and performing the first two of the three functions just mentioned, but not the third (except inconspicuously).

It is of course impossible to estimate the amount of movement of material. The fact that cummingtonite fibers penetrate pure quartz areas several millimeters shows that material was moved these distances. The preservation of microscopically thin bedding laminae of quartz, biotite, or carbonate suggests that little movement could have taken place except parallel to bedding. There are no definite veinlets of the rock minerals (except rare carbonate veinlets unrelated to this period).[35] Carbonate appears to have been the most mobile, but in most cases its movement was nil. How much of a part was played by diffusion is an open question.

In this light the puzzling distribution of cummingtonite in the Homestake formation and of tremolite-actinolite in the Poorman-DeSmet formation is less perplexing, the co-existence of carbonate and quartz somewhat reconciled, and the evidence for a closed system not controverted.

The solutions were probably connate water, possibly magmatic water, squeezed upwards from hotter depths along permeable shear zones or other channelways by compressive forces. Where rock permeability permitted movement of water, it doubtless offered ready escape to carbon dioxide. Thus, these two factors may have complemented one another.

*Equilibrium.*—Such paragenetic relationships as the incomplete destruction of garnet by cummingtonite, biotite, and chlorite, the partial replacement of cummingtonite by biotite and chlorite, and

[35] Table III, b.

the incipient development of chlorite at the expense of biotite and cummingtonite, indicate a system whose external conditions were changing more rapidly than internal molecular readjustment. They mean failure to meet equilibrium. Lowering of temperature was doubtless more important than changing pressure.

Still more compelling is the fact that quartz, sideroplesite, and cummingtonite exist side by side in the Homestake formation, and that quartz and dolomite occur together with tremolite in the Poorman-DeSmet formation. In the Northwestern formation and in parts of other formations where simpler changes took place, micaceous quartzites of the Ellison and Northwestern formations became adjusted through recrystallization of quartz and formation of biotite. Likewise pure dolomite beds attained equilibrium simply by recrystallization.

Possible reasons for the variableness of the metamorphism may be: (1) too rapid lowering of temperature; (2) irregular distribution of water (*a*) as a catalyzer to promote reaction, and (*b*) as a carrier of heat to raise the temperature above that required by cummingtonite and tremolite crystallization; (3) irregular distribution of favorable quartz-carbonate textures; (4) irregular distribution of permeability sufficient for the escape of carbon dioxide; and (5) irregular distribution of temperature resulting during folding.

Some thin sections contain pseudomorphs of sideroplesite after cummingtonite. They probably represent replacement by carbonate in solutions moving from some other place in the rock during the period of cummingtonite formation. However, the cummingtonite-building reaction might have been reversed by a local accumulation of carbon dioxide under high pressure from depth at a faster rate than its escape. "Secondary" quartz occurs in the slides but not in the pseudomorphs, as might be expected if the reaction had been reversed.

The lack of equilibrium places these rocks outside the mineral facies scheme of classification. They fit neither the green schist facies nor the amphibolite facies, which they resemble most,[36]

[36] Eskola, Pentti: The Mineral Facies of Rocks. Norsk Geol. Tidskrift, vol. VI, pp. 162–168, 1920.

cummingtonite having formed under one set of conditions, chlorite under another. Until it is demonstrated that more metamorphic regions attained equilibrium, the wide applicability of the mineral facies scheme must be questioned. The lack of parallelism between metamorphic effects shown by rocks of different composition is another difficulty apparent from this study.

The rocks of the Lead area straddle the Epizone and Mesozone of the Grubenmann classification.[37]

*Temperature, Pressure, Time.*—The main mineral sequence in the Homestake formation, garnet-cummingtonite-biotite-chlorite, is one of decreasing temperature.[38] Further, the temperature apparently lowered too rapidly for complete mineralogical readjustment. The " retrograde " metamorphism here demonstrated did not obliterate an earlier " progressive " metamorphism. Perhaps water was introduced into the system at a time when high enough temperature prevailed to permit the highest temperature (garnet-producing) reaction, or the introduced water supplied the necessary heat. The idea of a geologically sudden influx of water seems inescapable, unless the biotite- and chlorite-forming reactions depended upon the presence of cummingtonite and were held in abeyance until its formation. The relationship suggests the " reaction principle " of Bowen.[39] Biotite and chlorite, conceivably, could not form while iron and magnesium were held in the carbonate, because they were not stable at a sufficiently high temperature to increase the vapor pressure of carbon dioxide enough for its escape. Cummingtonite, stable at higher temperature, could do this; once it was formed, biotite and chlorite could form at its expense.

A possible cause of the rise of hot connate water was deep

[37] Grubenmann U. and Niggli, P.: Die Gesteinsmetamorphose, I. Allgemeiner Teil, p. 398. Gebrüder Borntraeger, Berlin, 1924.

[38] Eskola describes the occurrence of cummingtonite in transition zones between anthophyllite-cordierite rock and plagioclase gneiss in the outer aureole of a granite batholith (lower temperature occurrence than garnet, higher than biotite). (On the Petrology of the Orijärvi Region. Bull. Comm. Geol. Finlande, 40, p. 172, 1914.)

[39] Bowen, N. L.: The Evolution of the Igneous Rocks. Princeton University Press, 1928.

igneous intrusion. (If magmatic solutions also rose, they contributed nothing to the system at this stage.) Barrell[40] urged batholithic intrusion as a major factor in regional metamorphism. A pre-Cambrian batholith is known to underlie the Northern Black Hills.[41]

Cummingtonite doubtless crystallized well below the freezing points of magmas (between 570° C and 870° C for most),[42] and chlorite probably formed between 100° C and 300° C.[43] The temperature range embraced by chief crystallization in the Homestake formation was probably between 600° C and 300° C. Assuming a normal temperature gradient, these figures correspond roughly to depths of 14 to 6½ miles. It is likely, however, that all recrystallization occurred at a fairly shallow depth, say of 6 miles, the initial temperature having been raised by ascent of hot water, residual heat from folding, or similar cause.

An alternative possibility is that recrystallization persisted over a long period, and that it proceeded beneath an encroaching erosion surface. Under such circumstances cummingtonite and biotite might have crystallized at a depth of 14 miles and a temperature of 600° C, and chlorite at a depth of 6 miles and a temperature of 300° C. These depths imply pressures of 5800 atmospheres and 2500 atmospheres per square inch respectively (assuming a specific gravity of 2.7).

The time factor is even more elusive. It may well be that the space of time occupied by extensive recrystallization was greater than that occupied by the earlier mechanical movement. The effect of an advancing erosion surface on temperature and pressure during recrystallization metamorphism is an interesting speculation. If cooling through erosion is the faster process, it

[40] Barrell, Joseph: Relations of Subjacent Igneous Invasion to Regional Metamorphism. Amer. Jour. Sci., (5), vol. 1, pp. 1–267, 1921.

[41] Ferguson, H. G., and Turgeon, F. N.: An Occurrence of Harney Granite in the Northern Black Hills. Harvard Coll. Mus. Comp. Zool., Bull. XLIX, No. 5, 1915.

[42] Larsen, E. S.: The Temperature of Magmas. Amer. Min., vol. 14, pp. 81–94, 1929.

[43] Lindgren, Waldemar: Mineral Deposits, pp. 528, 598. McGraw-Hill Book Co., New York, 1928.

may check the other. This effect would tend to prevent the attainment of chemical equilibrium.

### HYDROTHERMAL METAMORPHISM.

*Distinctive Features.*—Sharply contrasted with the conditions of regional recrystallization during and following folding were the conditions surrounding the local hydrothermal metamorphic changes accompanying the emplacement of gold. Here was an open system constantly changing in composition, where moving solutions introduced large quantities of foreign materials which they substituted for old.

*Spatial Relations of Hydrothermal Minerals.*—A rude zoning of hydrothermal minerals exists about certain quartz masses in the Homestake formation. These irregular quartz veins range in size from an inch or less to fifty feet in thickness. Groups of these bodies persist from level to level in the Homestake mine, although individual bodies do not appear to be continuous for long distances. Locally they conform to schistosity. Elsewhere they are cross-cutting. Many cross the upper contact of the Homestake formation into the Ellison formation, where they are unaccompanied by ore. They are not so numerous or so large in the underlying formations. Whether their prominence in the Homestake formation is due to characteristics of mineralogy or permeability is not known. Arsenopyrite and chlorite decrease steadily in amount from the vein walls in a direction away from quartz; pyrrhotite occurs most abundantly at some distance from quartz and then decreases in amount more gradually away from it. The arsenopyrite zone near margins of quartz bodies is consistently high in gold. Strongly chloritized rock is generally gold-bearing.

Ideal zonal arrangement of minerals is seldom encountered, for the distribution about many veins was interfered with by nearby quartz masses that served as local centers or by the differential permeability (or other inhomogeneity) of the wall rock which allowed solutions to migrate farther in one direction than another. Nevertheless, the general relationship can scarcely be questioned.

It is significant that practically all hydrothermal quartz occurs in veins and that the veins, except for minor amounts of ankerite, contain practically nothing but quartz. Inclusions of wall rock in veins, however, contain chlorite, arsenopyrite, and sulphides. There is no evading the conclusion that all the solutions responsible for the hydrothermal minerals were in some places confined to the channelways now irregularly enlarged by replacement and occupied by quartz. The spatial distribution of the minerals suggests some selective straining effect of the wall rock and raises many interesting problems beyond the province of this paper.

*Nature of Solutions.*—That large quantities of materials were contributed to mineralized areas by moving solutions is obvious. That essentially equal amounts of original materials were removed is a necessary inference. The difference in chemical composition of original and introduced minerals shows that the ore solutions were not in equilibrium with the host rock at the time of introduction.

Quartz veins testify to the contribution of large amounts of $SiO_2$. Arsenopyrite and pyrrhotite prove the addition of As and S. Small amounts of apatite show that Ca and $PO_4$ (and Cl or F) were introduced. Extensive chloritization of cummingtonite schist in ore zones indicates the introduction of considerable $Al_2O_3$ as well as $H_2O$, because the initial content of $Al_2O_3$ and $H_2O$ as represented by biotite, garnet, and rock chlorite, was inadequate to yield the amount of hydrothermal chlorite present. The major exchange when chlorite replaced biotite was the substitution of more $Al_2O_3$ for $K_2O$. When chlorite replaced cummingtonite, it was the substitution of $Al_2O_3$ and $H_2O$ for $SiO_2$ (the Fe/Mg ratio is the same for the two). The replacement of garnet involved chiefly substitution of $H_2O$ and MgO for $SiO_2$. Only insignificant quantitative changes were effected by recrystallization of rock chlorite to hydrothermal chlorite. It can be concluded that some FeO, $Fe_2O_3$, MgO, $Al_2O_3$, $SiO_2$, and $CO_2$ of rock minerals were utilized in place to form hydrothermal minerals.

The solutions appear to have contained $H_2O$, $SiO_2$, FeO, $Fe_2O_3$,

$Al_2O_3$, CaO, MgO, S, As, $CO_2$, (F or Cl), and Au which were not derived from immediate rock walls. It is impossible to say how much of some of these materials was acquired by the solutions elsewhere as a result of other reactions with the enclosing rock. The major net exchange with wall rock was such that solutions became enriched in $SiO_2$ and impoverished in all else. Only at quartz veins was the wall rock enriched in $SiO_2$ and the solutions impoverished. The Homestake is unlike many other gold mines in ferromagnesian rocks in that sericitization with enrichment of the wall rock in $K_2O$ is lacking.

*Source of Solutions.*—The mineralogical changes wrought by the hydrothermal solutions are those common to ore deposits definitely associated with igneous sources. The ore solutions were probably late products of differentiation of the granite magma underlying the region.[44] In this the writer is in agreement with Paige,[45] Connolly,[46] and McLaughlin.[47]

The amphibolites are unrelated to the ores as to distribution. They were intruded during folding; the ores were introduced after folding. Except that the two may have risen from the same source, they are not believed to be genetically related.

The Tertiary dikes which cut through the ore bodies introduced negligible quantities of pyrite, calcite, fluorite, and quartz at their margins but are regarded by most workers as having no part in the gold mineralization. Hewett,[48] Hosted and Wright,[49] and Moore,[50] have argued that the Homestake ore is Tertiary, but the

[44] Ferguson, H. G. and Turgion, F. N.: *Op. cit.*

[45] Paige, Sidney: The Geology of the Homestake Mine. ECON. GEOL., vol. 18, p. 236, 1923.

[46] Connolly, J. and O'Harra, C.: The Mineral Wealth of the Black Hills. So. Dakota Sch. of Mines Bull. 16, p. 105, 1929.

[47] McLaughlin, D. H.: Ore Genesis and Structure (chapter of "The Homestake Enterprise"). Eng. and Min. Jour., vol. 132, pp. 324–329, (7), 1931; also review of Tertiary Mineralization of the Northern Black Hills by J. Connolly., ECON. GEOL., vol. 23, pp. 337–341, 1928.

[48] Hewett, G. C.: The Geological Age of the Homestake Lode. Eng. and Min. Jour., vol. 75, pp. 563–564, 1903.

[49] Hosted, J. O., and Wright, L. B.: *Op. cit.*

[50] Moore, E. G.: Geological Age of the Homestake Ore Bodies. ECON. GEOL., vol. 20, pp. 604–605, 1925.

early observations of Devereaux [51] and Irving [52] and the more recent work of Connolly,[53] Gibson,[53] McLaughlin,[53] Paige,[53] and Yates [54] overwhelmingly supports the view of pre-Cambrian mineralization. The reader is referred to papers by Connolly and McLaughlin for summaries of the evidence. The relationship between gold and pre-Cambrian vein quartz and chlorite (as well as arsenopyrite and sulphides) is convincing proof to the writer that if any gold in the Homestake ore bodies is Tertiary, it is insignificant in amount.

*Equilibrium.*—In an open chemical system like that existing when hydrothermal solutions carrying $SiO_2$, $Al_2O_3$, $Na_2O$, FeO, S, Au, and other ingredients were moving through permeable parts of the Homestake formation, the tendency is for the chemical system to change in composition until there is equilibrium between solutions and enclosing rock.

Highly chloritized rock adjacent to veins illustrates the closest approach to equilibrium anywhere achieved. Chlorite intermediate in character between typical rock chlorite and typical hydrothermal chlorite is found mostly in barren rock containing a sprinkling of sulphide grains, where it occurs as partial pseudomorphs after biotite, and as irregular patches replacing cummingtonite. It never exists as a wholesale replacement of the rock, as does typical hydrothermal chlorite near veins. Green biotite in several instances was found in similar rock, whereas it was not found in either highly mineralized or entirely unmineralized rock. It sometimes appears to grade into chlorite. Green biotite had lower indices of refraction than brown biotite accompanying it, in the two comparisons that were made. It is therefore probably lower in FeO, just as "intermediate" chlorite is lower in FeO (or $Fe_2O_3$) than most rock chlorite. They are correspondingly higher in $Al_2O_3$.

[51] Devereaux, W. B.: The Occurrence of Gold in the Potsdam Formation, Black Hills, South Dakota. Trans. Amer. Inst. Min. Eng., vol. 10, pp. 464–475, 1882.

[52] Irving, J. D.: A Contribution to the Geology of the Northern Black Hills. Ann. New York Acad. Sci., vol. 12, pp. 187–340, 1889.

[53] *Op. cit.*

[54] Yates, A. B.: Unpublished Doctor's thesis, Harvard University, 1931.

These observations suggest that both "intermediate" chlorite and green biotite may be products of reaction between long-travelled and devitalized or stagnant hydrothermal solutions and brown biotite and cummingtonite, which were extremely susceptible to alteration. Less $Al_2O_3$ was contributed and less FeO and $SiO_2$ were removed than close to veins, where fresher solutions acted upon the same minerals.

Important is the fact that parts of the Homestake formation composed chiefly of iron-magnesium carbonate and quartz are practically everywhere barren, whereas parts of the formation composed chiefly of iron-magnesium silicates and quartz are locally rich ore. In carbonate rock, not only is gold lacking, but hydrothermal chlorite and metallic minerals are difficult to find, although quartz veins are as large and as numerous as in (altered) cummingtonite schist. During the field mapping, only one case was found of carbonate-rich rock containing conspicuous hydrothermal chlorite and arsenopyrite. Both minerals were concentrated within a few inches of a quartz vein and were present only in small amounts. The prospect was previously sampled with discouraging results. Ore stops against carbonate rock in many cases in the Homestake mine.

Obviously the requirements for equilibrium or the possibilities of attaining it were different for mineralogically different kinds of rock, even though the chemical composition (save for $CO_2$ and $SiO_2$) was the same. Iron-magnesium silicates were a prerequisite for reaction between ore solutions and wall rock. Conceivably, the temperature of ore solutions was not high enough to elevate the vapor pressure of $CO_2$ of sideroplesite sufficiently for it to escape. Consequently there was limited reaction between ore solutions and carbonate rock. On the other hand, the temperature and pressure were such as to favor reaction with silicates where high vapor pressures were not contended with. The close (and entirely baffling) dependence of gold upon hydrothermal chlorite prevented its deposition in carbonate rock not previously converted to chlorite schist. (It is not established whether the removal of $Al_2O_3$ from solution to form chlorite

simultaneously caused the precipitation of gold, or whether chlorite acted as a precipitant to gold in a later stage.)

On these grounds alone can be seen a reason for the mineralization of those parts of the Homestake formation containing silicates and for the lack of mineralization of carbonate rock in the Homestake and other formations. The Upper Ledge formation may contain less ore than the Homestake formation partly because in the mine it contains more carbonate and quartz, and less cummingtonite, biotite, and chlorite.

The silicates of other formations on the whole contained more $Al_2O_3$ than those of the Homestake formation, since cummingtonite contains practically none. The wholesale substraction of $Al_2O_3$ from solution to form chlorite was therefore prevented, and possibly for this reason gold was not precipitated in them. The superior permeability of the Homestake formation, however, was probably a more important reason.

A puzzling fact is that Homestake rock containing very abundant cummingtonite in the crests of some anticlines is notably barren, although ore occurs just north of it. From mineralogical and structural grounds these places would appear to be the most favorable loci of ore. Perhaps here such complete cementation took place during regional recrystallization as to render the rock impermeable to later hydrothermal solutions. This type of rock contains fewer quartzite layers and pods, the silica having been utilized in the formation of cummingtonite. Rock with abundant quartzite layers appears to have been the most permeable.

## SUMMARY.

The gold-quartz ore bodies of the Homestake mine are replacement bodies confined to one pre-Cambrian metamorphosed sedimentary stratum termed the Homestake formation. This relationship, the general geology of the Lead area, and the mineralogy of the ores, have been previously described.

*Mineralogy.*—The Homestake formation was a sandy, clayey iron-magnesium carbonate sediment. During regional metamorphism, garnet, cummingtonite, biotite, and chlorite were

formed in the order named. Later ore solutions locally precipitated quartz in large veinlike masses, and near them ankerite, chlorite, arsenopyrite, pyrrhotite, pyrite, minor constituents, and gold. The original carbonate is sideroplesite; the hydrothermal carbonate is ankerite. Hydrothermal chlorite generally possesses lower refractive indices than rock chlorite.

Some of the original sedimentary quartz exists as small grains which retain the general shape of sand grains. Larger irregular grains resulted from the recrystallization of these. Each of these types has a poorly developed individual tendency toward crystallographic and dimensional parallel orientation lacking in a third type, fine-grained recrystallized interstitial quartz. Cummingtonite formed from a reaction between quartz and sideroplesite. The major recrystallization of the formation resulting in new minerals followed the cessation of folding movements and preceded the advent of ore solutions.

*Regional Metamorphism.*—The incompleteness of the chemical changes within the Homestake formation during regional metamorphism—shown by the irregularity of cummingtonite distribution—indicates lack of equilibrium. Sedimentary differences, differential permeability of rocks to $CO_2$, and differences in temperature and pressure from place to place due to folding, all fail to explain cummingtonite distribution, in the opinion of the writer. Irregularly distributed water acting as a carrier of heat and as a catalyzer was probably necessary for the reaction. Anticlinal crests contain the most abundant cummingtonite, a relationship suggesting that upwardly-squeezed hot connate (?) water was structurally localized.

Concomitant variations in the composition of rock minerals, shown by plotting refractive indices and the constancy of the Fe/Mg ratio in sideroplesite, cummingtonite, and chlorite, suggest that the chemical system remained essentially closed except for the escape of $CO_2$. Although solutions were capable of movement, there was no significant movement of material.

The lack of equilibrium prevents the application of the mineral facies conception. The rocks as a whole approximate an iso-

physical series. The Homestake formation approximates an isochemical series.

The mineral sequence denotes decreasing temperature. The lack of "progressive" mineralogic changes necessitates the consideration of either a geologically sudden influx of hot water, due possibly to the heating of connate water by deep intrusion of the granite batholith which underlies the Black Hills, or the obedience to a "reaction principle." Biotite and chlorite possibly were unstable at temperatures adequate for reaction with carbonate. Cummingtonite was able to form. Biotite and chlorite formed from it at a lower temperature.

*Hydrothermal Metamorphism.*—The physical-chemical conditions of hydrothermal metamorphism were markedly different from those of regional metamorphism. An open chemical system prevailed during which material was introduced and exchanged by moving solutions.

The spatial arrangement of arsenopyrite, pyrrhotite, and chlorite about large quartz bodies suggests a mechanism of selective migration through rock. The writer, like Paige and others, regards the ore solutions as coming from the underlying pre-Cambrian batholith.

Cummingtonite schist close to quartz masses is extensively chloritized locally and contains abundant metallic minerals and gold. Carbonate-quartz schist is barren and lacks hydrothermal minerals, although quartz veins occur in it. Possibly the temperature was not high enough for reaction between solutions and carbonate. Gold, which is associated with chlorite, is therefore absent.

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# DISSEMINATED GALENA IN THE UPPER CAMBRIAN OF THE CENTRAL MINERAL REGION, TEXAS.*

CHARLES LAURENCE BAKER.

THE occurrence of galena in the Upper Cambrian of Central Texas was first mentioned 40 years ago,[1] but its importance in the problem of the lead and zinc ores of the Mississippi basin has apparently been overlooked by most, if not all, investigators. No extensive investigation of the Texas deposits has ever been made, and they have been very little prospected. The writer's observations have been confined to the district in the Pedernales River valley in western Blanco County.

Only one new area seems to have been prospected since 1890; the three widely separated localities previously noted by Comstock are in areas around the margins of the pre-Cambrian crystallines. One is on the northeast margin on Silver and Beaver creeks in northwestern Burnet County, the second lies between Little Bluff and Honey creeks in central Mason County, and the third is on Pedernales River in western Burnet County. Each locality is separated from the others by distances of from 50 to 60 miles. The locality prospected in later years is one mile north of Slaughter Gap and four miles north of Marble Falls, Burnet County. This is near a fault and exhibits considerable secondary galena in small veinlets.

*Occurrence of Galena.*—The four occurrences are in the Cap Mountain limestone, supposedly equivalent in age to the Bonne-

* Published with the permission of the Director, Bureau of Economic Geology, University of Texas.

1 Comstock, Theo. B.: Report on the Geology and Mineral Resources of the Central Mineral Region of Texas. Geol. Surv. Texas, 2d Ann. Rept., pp. 583–590, 1891.

Other papers are: Phillips, W. B.: Lead Ore in Burnet County, Texas. Eng. and Min. Jour., vol. 77, p. 364, 1904. Paige, Sidney: Llano-Burnet Folio, U. S. Geol. Surv., 1912; and Mineral Resources of Llano-Burnet Region, Texas, U. S. Geol. Surv., Bull. 450, pp. 75–77, 1911.

terre formation of southeastern Missouri, where that limestone overlaps the lower Upper Cambrian Hickory sandstone and rests upon the slopes of granite hills or knobs which were islands in the Upper Cambrian sea at the time the limestone was deposited. The four crystalline knobs of the Pedernales valley are of coarse-grained granite containing bluish opaline quartz. In places the limestone rests on the granite without a basal conglomerate and extended search is necessary in order to find fragments of the granite in the limestone. In other places a basal conglomerate is found, composed of rounded pebbles and boulders of the granite with a matrix of limestone. Comstock considered the granite to be intrusive into the limestone, probably because the limestone dips at considerable angles away from it. The prospecting appears to have been based on the assumption of an intrusive contact, since all of it has been done on or near the junction of granite and limestone, but the writer has found galena in the limestone a mile from the nearest granite outcrop. There has been very little extensive prospecting here as well as elsewhere in Texas because the minerals are owned by the proprietors of the surface. Therefore, there is not the incentive for prospecting afforded by areas in which public lands, on which royalty is not exacted, are available to the seeker of mineral deposits.

It appears to be an important fact that the Texas galena occurs in carbonate rocks, and, moreover, in rocks containing considerable quantities of glauconite. As is well known, glauconite is almost universally distributed in the earlier deposits of the Upper Cambrian seas wherever they are now exposed in the area between the pre-Cambrian shield on the north, the Ouachita-Marathon mountain system on the south, the Appalachians on the east and the eastern Rocky Mountains on the west.

So far as the writer has been able to determine, the galena of central Texas is syngenetic, having been deposited with the limestone and glauconite in the Upper Cambrian sea. The galena occurs as cubes that vary in size from microscopic up to one inch across, although it is reported on apparently trustworthy evidence

that masses of solid galena as large as a cubic foot have been found. These larger masses may be secondary concentrations. In only two instances has the writer noted secondary or subsequently concentrated galena, one in a thin veinlet occupying a stylolite plane of solution and one in small solution cavities. With these exceptions, the galena occurs irregularly disseminated in the original dense, unaltered, finely crystalline gray limestone, where it appears to be fully as syngenetic as the glauconite in the same limestone. The limestone in places contains small cavities, either empty or calcite-filled, and thin seams along stylolite planes where the glauconite has been concentrated upon solution of the limestone. Cerussite is found in small amount, lining solution cavities in the limestone subjected to surficial solution. The galena-bearing limestone weathers on the surface to dark yellowish brown or tawny yellow. Small quantities of pyrite and chalcopyrite are also disseminated in the galena-bearing rock. The rock richest in galena has as much as five per cent in volume of the mineral but most of the limestone, so far as observed, contains less than that amount. Fragments chipped from outcrops almost anywhere in the vicinity of the granite knobs will show crystals of galena.

*General Geology.*—It is desirable, in order that the reader may have a fuller understanding of the occurrence, that the geologic history and structure of the area be summarized briefly. The Upper Cambrian sea advanced over a somewhat uneven, hilly topography, in the depressions of which was deposited the oldest formation, the Hickory sandstone. The Hickory is generally conglomeratic at its base; the higher beds are white, red, or brown, siliceous and calcareous sandstone carrying glauconite. It grades upwards through calcareous sandstone into the predominant limestone of the Cap Mountain formation. Much of the red and brown color of the Hickory appears to have been derived from alteration of the glauconite and oxidation of its iron content. Even the apparently unaltered glauconite in this and the succeeding Cambrian formations will, when struck with the hammer, emit a red powder of hematite. In many places,

the strata richer in glauconite have been changed to brownish-black or red, hard, dense and heavy limonite or hematite which forms the matrix of sand grains. The matrix of the sand grains in such places was originally glauconite, and still remains so where the glauconite has not been decomposed. Paige thought that the glauconite probably originated through " the decomposition of abundant potassium feldspar with iron in solution," both being plentiful in the pre-Cambrian rocks of the region.

The Cap Mountain limestone is thin, averaging perhaps 90 feet in thickness, with bluish and grayish, glauconitic, and locally sandy limestone succeeded by glauconitic, calcareous sandstone. It is overlain by the Wilberns, which is predominantly limestone but consists largely of shale in the upper third, with more limestone at the top. There are several lentils of conglomerate in the shaly part. The Wilberns ranges up to more than 200 feet in thickness.

The Ellenburger limestone rests apparently unconformably upon the Wilberns, transgressing by overlap, at least locally, over eroded surfaces of the Wilberns. Dake and Bridge [2] have recently shown that the Ellenburger ranges in age from the Potosi to the Cotter of the Ozark section, with apparently one or more faunal zones present which are not yet known in Missouri. They state that the maximum thickness approaches 2000 feet. The Ellenburger contains a number of horizons of dolomite and much white and yellow chert. It is commonly much brecciated, honeycombed by solution, and there has been much differential solution parallel to the bedding, forming numerous stylolites. The outcrop surfaces locally have much residual chert, which is abundant in the basal Mississippian conglomerate.

No middle Paleozoic strata are known. The full extent of the Mississippian has not yet been determined but on the north flank of the crystalline exposures, at least locally, thin horizons of both Boone and Chester age have been found. These Mississippian rocks are shales, limestones, and conglomerates.

The Lower Pennsylvanian, or Bendian, apparently covered all

[2] Dake, C. L., and Bridge, Josiah: Faunal Correlation of the Ellenburger Limestone of Texas. Bull. Geol. Soc. Amer., vol. 43, pp. 725–728, 1932.

the flanks of the area and may have reached over the center. Locally, the basal Pennsylvanian Marble Falls limestone may rest, commonly with a basal conglomerate or breccia of chert, directly upon the Ellenburger, but it is yet uncertain whether such basal strata are Marble Falls, at least in all cases. The Marble Falls is a hard dense siliceous limestone, characterized by abundant dark to black cherty nodules, and ranging up to 450 feet in thickness. It, as well as the conformably overlying Smithwick dark shale, and the Mississippian Barnett shale, are very bituminous and produce oil on the Bend Arch north of the outcrops. The Smithwick is the thickest shale formation of the Central Mineral or Llano region. Only a remnant of it is preserved but there are sections that reach nearly 400 feet in thickness.

Subsequent to the deposition of the Smithwick and before that of the middle Pennsylvanian Strawn formation, the area was uplifted, gently folded, and considerably faulted and eroded. The fault displacements are predominantly vertical and vary up to a maximum of 1800 feet in amount. Most of the folds and faults have a northeast trend with a situation on the northwest flank of the Ouachita-Marathon mountain system, which has undergone much greater deformation farther to the southeast. There was later movement, displacing the Strawn formation, on the longest fault zone known in the area, which extends about 60 miles from northern Gillespie County to the Colorado River at the Mills-San Saba county line. Part of the north half of this fault zone trends west of north, giving the only exception to the northeastward trends, and the greatest known fault displacement in the area is where this zone turns from north of east to due north. The structures in the pre-Cambrian rocks of the area have a north-northwest strike.

The quaquaversal dips of from 5 to 15 degrees in the Upper Cambrian encircling the granite knobs are produced by one or more of the following: (*a*) original depositional dip, (*b*) anticlinal arching, and (*c*) greater solution of the limestone in the synclines. Differential compaction is apparently ruled out, because only limestones and sandstones occur in this part of the section or beneath it.

The largest springs of the region occur along the faults that cut the sedimentary rocks. Analyses of large quantities of the spring waters from such fault springs as those of the Little Llano and Pedernales rivers and, in Mason County, of Honey and Mill creeks and James River, might show appreciable quantities of lead and perhaps of other metals.

The Middle Pennsylvanian Strawn formation of sandstones, shales, and conglomerates flanks on the north and east the uplift of older rocks, and the later Pennsylvanian formations consisting of limestones and terrigenous sediments flank it on the west. It is doubtful, however, if these strata ever covered the top or the south and southeastern flanks of the uplift. It is also doubtful if the area of pre-Strawn rocks was covered by Permian, Triassic, or Jurassic strata, the probability being that it was eroded during those periods.

The sea again covered the area near the end of the Lower (Neocomian) Cretaceous and the cover of Cretaceous sediments probably persisted to some time during the Pliocene, when drainage lines superimposed on the Cretaceous strata cut beneath them and began to exhume the Paleozoic and pre-Cambrian rocks.

The lower gravels and sands of the Cretaceous, of the Strawn and later Pennsylvanian formations, the upper Cap Mountain sandstone and the Hickory sandstone are important horizons of artesian water. The various Paleozoic limestones, more particularly the Ellenburger, also have had and still have fairly abundant underground water. The numerous faults allow fairly extensive mingling of the waters of different horizons.

*Localization of Ore.*—If profitable deposits of lead exist in central Texas it is probable that they will occur in synclines, or at least in places down the dip from the Cap Mountain outcrops. Such enriched deposits will be either residual concentrations effected by the solution of the enclosing limestone, or an enrichment through the deposition of ore in solution planes, cavities, or fractures, or a combination of the two processes. The Cap Mountain and Wilberns limestones are fractured by jointing and faulting but for some reason appear to be less fractured than the overlying Ellenburger. The Ellenburger exhibits more solution

effects than the underlying limestone; it contains a number of large caverns, is more honeycombed, and has more stylolites. Shale cappings, which might have inhibited free upward passage of solutions and brought about ore deposition immediately underneath, are the upper Wilberns, the Barnett, and the Smithwick. However, the shales would serve as impervious cappings mainly before the faulting took place, which occurred near the end of the lower Pennsylvanian. Perhaps neither the Barnett nor the Smithwick covered more than some of the flank areas. If the main deposition of ore took place after the faulting, anticlinal conditions would be most favorable, provided the presence of an imprevious shale cap is necessary. This would depend, however, upon the presence of reducing solutions, or of some other factor favorable for precipitation of ore. If Siebenthal's [3] theory for the formation of the lead ore in the Joplin district is accepted, the outcropping part of the chert breccia at the top of the Ellenburger, which is in places directly beneath the Barnett shale and in other places directly beneath the Marble Falls limestone, would be a favorable site for ore deposition, especially on the north flanks of the Llano uplift where the Barnett is known to be present as well as farther north underneath the Bend Arch. But the areas of the separate fault blocks are relatively small, and collecting areas for ore are insignificant. Moreover, ore-bearing solutions, if existent, had free exit to the surface from near the close of the Lower Pennsylvanian to near the close of the Lower Cretaceous, and deposits formed at or near the surface during that immense interval of time were subsequently removed by erosion both during the same interval and in the later Cenozoic. During the latter, at least, erosion was vigorous.

It is perhaps significant that the writer has found galena and other metallic minerals in Upper Pennsylvanian and Permian rocks of Texas far to the north and northwest of the Llano area, and even farther away from any known igneous rocks later in age than pre-Cambrian. Galena, sphalerite, and chalcopyrite occur in the fossiliferous limestone roof of a coal bed in a mine near Loving, Young County, Texas, and galena occurs in Permian

[3] Siebenthal, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Surv. Bull. 606, 1915.

dolomites in Hardeman and Fisher counties, Texas. Copper ores are widely distributed in the Permian and Triassic red beds of Texas, New Mexico, and Arizona.

*Origin.*—If the galena in central Texas is syngenetic in the Upper Cambrian limestone, there are some pertinent facts that possibly have bearings on the origin of the mineral in the Mississippi Basin. One is the association of the galena with carbonate rocks, either limestone, or magnesian limestone, or dolomite. Another is its association with glauconite. A third is that the Upper Cambrian sea covered a third of the United States in the first marine incursion after the pre-Cambrian. Because the Lipalian Interval of denudation preceding the Upper Cambrian incursion was of vast duration, residual or other surface deposits of lead compounds, derived from an original pre-Cambrian source, had ample chance to accumulate in appreciable quantities. These would go into solution or suspension in the Cambrian sea or be brought to it in either form, or else be carried in as detritals. Deposition of the galena would take place wherever conditions were favorable. These conditions may have been those of shallow water, or the littoral in which precipitation of suspended colloids occurred by mingling of waters of different chemical content in currents, or of land waters with those of the sea, or the lead compounds in solution may have been precipitated where carbonates and glauconite were forming, or where mechanical wave wash caused aeration of the water and abstraction of either the hydrogen or some other molecule in the soluble compound, thereby rendering it insoluble. Or, detrital fragments of galena may have served as nuclei which by mass action or some other process caused addition of galena to them, either from lead compounds carried in solution or suspension in the shallow waters. There will doubtless be objections to any or all of these surmises, yet it is perhaps well to advance them in the possibility that one or more of them might be a contribution to a complex and difficult subject.

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# THE CAUSE OF BRITTLENESS IN CHRYSOTILE ASBESTOS.*

N. D. SOBOLEFF AND M. V. TATARINOFF.

CHRYSOTILE-FIBER may be described as normal, harsh, and brittle.[1] In the last-named, the fibers are hard to the touch and break easily when bent. Under the microscope no difference in the optical properties of these varieties is observed. In the material from some sources the average index for $\gamma$ is 1.550, for $\alpha$ 1.540, but in some cases it drops to 1.510 for $\alpha$ and 1.520 for $\gamma$. In the individual occurrences the indexes both of refraction and double refraction are identical for normal and brittle chrysotile-asbestos.

No appreciable difference has been observed in the chemical analyses of the normal and brittle chrysotile-asbestos, although in some cases a certain drop in the content of contained water, and in other cases the presence of lime, have been noted for the brittle variety.

A number of different explanations have been advanced to explain the cause of brittleness in some chrysotile fibers. F. Cirkel (10, 31)[2] in discussing Canadian occurrences, believes that brittle fiber may be due to exposure to high temperature, and Donald (12, 61) states that soft fiber loses some of its combined water at high temperatures, and becomes brittle. Bateman (9, 670) noted that the chrysotile-asbestos of the Sierra Ancha region, Arizona, showed all stages in transition between silky and harsh varieties, although they did not differ much chemically. The only point of difference he finds is that the brittle fibers contained .10 per cent. CaO. He also says:

> Examination so far has not shown conclusively the cause of this unusual variety of chrysotile. Chemically and optically it cannot be dis-

* Rewritten by H. Ries.

[1] Some authors recognize semi-brittle and semi-harsh varieties.

[2] Figures in parentheses refer to bibliography at end of article.

tinguished from the silky variety. I am inclined to believe that it represents either another variety of chrysotile or an incompleted stage of transformation of massive serpentine to chrysotile, or that the harshness may be due to a later infiltration of serpentine (retinalite) around the chrysotile fibers.

J. S. Diller (11) states that the probable cause of the brittleness lies in the fact that thin films of calcite are deposited between the fibers of chrysotile.

In his description of chrysotile-asbestos occurrences in the Amiando mines on the island of Cyprus, Sagui (15) makes the suggestion that pressure was the main factor in the formation of harsh fibers, for the brittle fiber appears only in the lowest levels.

In his description of the Bagenovsky asbestos occurrence in the Urals, P. M. Tatarinoff (7) supposes that the brittleness of fiber is due to the fact that it separates into the finest fibers less easily than does the silky variety. The same author (6), in his description of the Ostanin deposits in the Urals, and V. V. Tchernih (8), in describing the Bagenovsky occurrence (also in the Urals), attribute the brittleness to the presence of CaO, which is shown in chemical analyses.

It will be seen from the opinions noted above that the cause of brittleness in chrysotile fibers has not been conclusively proved, and that chemical analyses alone are used as a basis of interpretation. Keep (13) seems to have shown rather conclusively from his field investigations that brittle asbestos is but a transition stage between normal asbestos and talc. In the latter there are veins consisting of pseudomorphs of talc after asbestos. Keep has made numerous chemical analyses of both types of chrysotile-asbestos, and has attempted to interpret them. However, his method of calculating these analyses into the mineralogical composition has not given positive results, although he remarks (13, 111) that "with a decrease of the serpentine constituent and an increase of talc, corresponding to a decrease in combined water and an increase in silica, the fibers become brittle."

N. D. Soboleff (5), in discussing the Iltchirsk occurrence of chrysotile-asbestos, situated in the Booriat-Mongolian Republic, has noted a great resemblance to the Rhodesian occurrences.

In the transition zone between serpentine containing veins of normal chrysotile-asbestos and talcose carbonates, there are veins of asbestos completely replaced by pseudomorphs of talc. Along with these, a transition from brittle asbestos into talc is observed, in some cases in the same vein, with pseudomorphs of talc.

TABLE I. COMPOSITION OF NORMAL FIBER.

| | Occurrence | No. of Analyses | Chemical Composition | Author and page |
|---|---|---|---|---|
| 1. | Bagenovsky | 2 | $358H_4$ $Mg_3Si_2O_9+$ $2H_2O$ | 8-35 |
| 2. | " | 3 | $350H_4$ $Mg_3Si_2O_9+$ $9ZH_2O$ | 8-35 |
| 3. | " | 4 | $71H_4(H_2Mg)MgFe/Mg_3Si_2O_9+$ $Al_2O_3$ + $8H_2O$ | 8-35 |
| 4. | " | 5 | $34H_4$ $Mg_3Si_2O_9+(AlFe)_2O_3+$ $4H_2O$ $+2MgO$ | 8-36 |
| 5. | " | 8 | $88H_4(H_2Mg)(MgFeMnNi)Mg_3Si_2O_9+(AlFe)_2O_3$ $+5H_2O$ | 8-36 |
| 6. | " | 12 | $49H_4$ $(MgFe)$ $Mg_2Si_2O_9+(AlFe)_2O_3+18H_2O$ | 8-37 |
| 7. | " | 13 | $57H_4$ $(MgFe)$ $Mg_2Si_2O_9+(AlFe)_2O_3$ + $38H_2O$ | 8-37 |
| 8. | " | 14 | $352H_4$ $(MgFe)$ $Mg_2Si_2O_9+(AlFe)_2O_3+49H_2O$ $+32MgO$ | 8-37 |
| 9. | " | 18 | $8H_4$ $(MgFeNiMn)Mg_2Si_2O_9+(AlFe)_2O_3+H_2O$ | 8-38 |
| 10. | " | 19 | $8H(H_2Mg)$ $(MgFe)$ $Mg(SiTi)_2O_9+(AlFe)_2O_3+16H_2O$ | 8-39 |
| 11. | Iltchirsk | .. | $51H_4(H_2Mg)(MgFeNi)$ $MgSi_2O_9+(AlFe)_2O_3$ | 5-1190 |
| 12. | " | .. | $47H_4(H_2Mg)(MgFeNiMn)MgSi_2O_9+(AlFe)_2O_3+H_2O$ | 5-1190 |
| 13. | Bagenovsky | 7 | $51H_4(H_2Mg)(MgFeNi)$ $MgSi_2O_9+(AlFe)_2O_3+H_2O$ | 1-679 |
| 14. | " | 9 | $46H_4(H_2Mg)(MgFeNi)$ $MgSi_2O_9+(AlFe)_2O_3+6SiO_2$ | 1-679 |
| 15. | " | 11 | $23H_4(H_2Mg)(MgFeNi)$ $MgSi_2O_9+(AlFe)_2O_3+3SiO_2$ | 1-679 |
| 16. | " | 13 | $55H_4(H_2Mg)$ $MgSi_2O_9+(AlFe)_2O_3$ | 1-679 |
| 17. | " | 49 | $55H_4(H_2Mg)(MgFeNi)$ $MgSi_2O_9+(AlFe)_2O_3$ | 1-679 |
| 18. | Ostafin | 1 | $5OH_4(H\ Mg)(MgFe)$ $MgSi_2O_9+(AlFe)_2O_3$ | 6-33 |
| 19. | " | 2 | $3OH_4(H_2Mg)(MgFe)$ $MgSi_2O_9+(AlFe)_2O_3+3H_2O$ | 6-33 |
| 20. | Krasnouralsk | .. | $61H_4(H_2Mg)(MgFe)$ $MgSi_2O_9+(AlFe)_2O_3+2SiO_2$ | 3-36 |
| 21. | Arizona | 3 | $39H_4(H_2Mg)(MgFe)$ $MgSi_2O_9+(AlFe)_2O_3+12H_2O$ | 11-302 |
| 22. | Rhodesia | 42 | $24H_4(H_2Mg)(MgFeMn)$ $MgSi_2O_9+(AlFe)_2O_3+5H_2)$ | 13-108 |
| 23. | Canada | .. | $14H_4(MgFe)$ $Mg_2Si_2O_9+(AlFe)_2O_3+7H_2O+MgO$ | 10-31,80 |
| 24. | " | .. | $15H_4(MgFe)Mg_2Si_2O_9+(AlFe)_2O_3+$ $7H_2O+17MgO$ | 10-31,80 |
| 25. | " | .. | $43H_4(MgFe)$ $Mg_2Si_2O_9+(AlFe)_2O_3+10H_2O$ | 12-60 |
| 26. | Lookovskly | .. | $19H_4(H_2Mg)$ $(MgFe)$ $MgSi_2O_9+(AlFe)_2O_3+2SiO_2$ | 4-337 |

Soboleff has interpreted the chemical analyses of the asbestos from this occurrence according to the method of Professor K. I. Viscont, and F. B. Siromiatnikoff, while using this method and admitting the possibility of stoichiometric replacement of mag-

nesium by hydrogen and FeO, has come to the conclusion that for chrysotile-asbestos Tschermak's formula, which has been derived from serpentine by removing the oxides $(AlFe)_2O_3$, may be accepted.

All these statements have been used by Siromiatnikoff in his investigation of the chemical composition of the Bagenovsky chrysotile-asbestos. For normal fiber he has derived the formula

TABLE II. COMPOSITION OF HARSH FIBER

| | Occurrence | No. of Analyses | Chemical Composition | Author and page |
|---|---|---|---|---|
| 1. | Bagenovsky | 5 | $498H_4(H_2Mg)(MgFeMn)\ MgSi_2O_9+(Al\ Fe)_2O_3+113H_2O$ | 6-33 |
| 2. | " | 15 | $12H_4(H_2Mg)(MgFeMn)\ MgSi_2O_9+(AlFe)_2O_3+0.25SiO_2$ | 6-38 |
| 3. | " | 22 | $54H_4(MgFe)Mg_2Si_2O_9+(AlFe)_2O_3+8H_2O+5(MgFe)O$ | 8-39 |
| 4. | " | 23 | $355H_4(H_2Mg)(MgFe)\ MgSi_2O_9+Fe_2O_3+6SiO_2$ | 8-39 |
| 5. | " | 24 | $234H_4(H_2Mg)(MgFe)\ MgSi_2O_9+(AlFe)_2O_3+8SiO_2$ | 8-39 |
| 6. | " | 26 | $52H_4(H\ Mg)(MgCaFeNi)MgSi_2O_9+(AlFe)_2O_3+5SiO_2$ | 8-39 |
| 7. | " | 27 | $69H_4(H_2Mg)(MgCaFe)Mg(SiTi)_2O_9+(AlFe)_2O_3+6SiO_2$ | 8-39 |
| 8. | " | .. | $276H_4(H_2Mg)(MgFeNi)MgSi_2O_9+(AlFe)_2O_3+6.5SiO_2$ | |
| 9. | Ostanin | 4 | $37H_4(H_2Mg)(MgFe)\ MgSi_2O_9+(AlFe)_2O_3+SiO_2$ | 6-33 |
| 10. | Iltchirsk | .. | $38H_4(H_2Mg)(MgFeNi)MgSi_2O_9+(AlFe)_2O_3+2SiO_2$ | 5-1190 |
| 11. | Arizona | 5 | $101H_4(H_2Mg)(MgMn)MgSi_2O_9+(AlFe)_2O_3+9SiO_2$ | 11-302 |
| 12. | " | 2 | $38H_4(MgFe)Mg_2Si_2O_9+(Al_2O_3)+5MgO+3SiO_2$ | 11-302 |
| 13. | " | 4 | $35H_4(MgFe)Mg_2Si_2O_9+(Al_2O_3)+2MgO+3SiO_2$ | 11-302 |
| 14. | Rhodesia | 77 | $20H_4(MgFeNi)Mg_2Si_2O_9+(AlFe)_2O_3+8MgO+4SiO_2$ | 13-108 |
| 15. | " | 78 | $23H_4(MgFeMn)Mg_2Si_2O_9+(AlFe)_2O_3+MgO$ | 13-108 |
| 16. | " | 81 | $16H_4(MgFeNi)Mg_2Si_2O_9+(AlFe)_2O_3+1.6MgO+2SiO_2$ | 13-108 |
| 17. | " | 61 | $11H_4(MgFe)Mg_2Si_2O_9+(AlFe)_2O_3+MgO$ | 13-108 |
| 18. | " | 43 | $9.5H_4(MgFe)\ Mg_2Si_2O_9+(AlFe)_2O_3+2.5SiO_2$ | 13-108 |

Corrections to tables. Table I: No. 7, 39 is 32; No. 10, 8H is $8H_4$ and 16 is 1.6; No. 18, (HMg) is $(H_2Mg)$; No. 21, 12 is 1.2; No. 24, 17 is 1.7. Table II: No. 1, $MgSi_2O_9$ is $Mg_3Si_2O_9$; No. 6, (HMg) is $(H_2Mg)$; No. 8, 276 is 27.6; No. 16, $2SiO_2$ is $2.5SiO_2$; No. 18, 2.5 is 1.5.

$7OH_4(H_2Mg)(MgFe)MgSi_2O_9 + (AlFe)_2O_3$. After perfecting this method, Soboleff has obtained the following formula for the normal fiber of the chrysotile-asbestos from the Iltchirsk occurrence:

$$6OH_4(H_2Mg)(MgFe)MgSi_2O_9 + (AlFe)_2O_3 + H_2O$$

and for the brittle variety:

$$38H_4(H_2Mg)(MgFe)MgSi_2O_9 + (AlFe)_2O_3 + 2SiO_2.$$

Taking the above factors into consideration, we have calculated all the analyses known in the literature according to this method.

In most of the analyses there is a slight variation in the content of $SiO_2$, MgO, and $H_2O$. $Al_2O_3$ and $Fe_2O_3$ appear in nearly all of them. Small amounts of $K_2O$ and $Na_2O$ are present, but they can hardly be of importance in the chemistry of chrysotile-asbestos and are probably accounted for by contamination by ground waters, as well as the organic impurities. As for brittle asbestos, the CaO is not necessarily present in its composition, therefore the belief that it is responsible for the brittleness of chrysotile-asbestos has no foundation.

In making the calculations, we have used the following oxides: $SiO_2$, $Al_2O_3$, $Fe_2O_3$, FeO, MgO, CaO, $H_2O$, MnO, $Cr_2O_3$, NiO, $TiO_2$. The minerals stated by the authors to be present in appreciable amounts, such as magnetite, calcite, magnesite, nontronite, and chromite, were first removed, the remaining oxides were then recalculated to 100 per cent., and the number of molecules available for the chrysotile formula calculated accordingly. Expressing the mineral composition in this chrysotile-asbestos formula, we obtain the following chemical composition for the normal (Table I) and brittle (Table II) fibers.

These facts are in agreement with the field data in that the brittle fiber may be considered as a transition between normal chrysotile-asbestos and talc. Taking a molecule of chrysotile-asbestos as 100, we proceeded to calculate the remaining oxides. The average obtained for normal type was $3.3(AlFe)_2O_3$, $12.6H_2O$; and for the brittle variety, $3.8(AlFe)_2O_3$, $6.4SiO_2$.

## SUMMARY.

1. On the basis of the field investigations of the Rhodesian and Iltchirsk occurrences of chrysotile-asbestos it may be conclusively stated that brittle asbestos is a transition stage not between serpentine and normal asbestos but between the latter and talc.

2. In most cases normal asbestos contains an excess of water.

3. Brittle chrysotile-asbestos (*a*) is characterized by an excess of $SiO_2$ and occasionally MgO; (*b*) it may be regarded as a prod-

uct of metamorphism of normal chrysotile-asbestos; (*c*) the explanation of the brittleness by the presence of CaO in the chemical composition of asbestos, *i.e.* by the isomorphous replacement of MgO, is inconclusive.

Moreover, in most of the analyses containing CaO, $CO_2$ is present in more or less quantity, which definitely shows an admixture of calcite. Only in analyses 26 and 27, made by V. V. Tchernih on samples of the Bogenovsky occurrence, and showing 8 to 9 per cent. CaO, is there a departure from the general scheme. However, the fact that the chemical analysis of brittle chrysotile-asbestos, the accuracy of which is beyond doubt, was made on a sample from the same claim to which the authors make reference, makes the presence of CaO in Tchernih's analysis rather dubious. In no other occurrence have we discovered the presence of CaO in any appreciable quantity.[3]

Field observations on the formation of brittle asbestos due to its change into talc are confirmed by our method of calculation.

Moscow, U. S. S. R.

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[3] In Siromiatnikoff's collection there are three more analyses of brittle asbestos, which so far have not been published. In none of them is CaO present.

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# QUANTITATIVE MICROSCOPIC METHODS WITH AN INTEGRATING STAGE APPLIED TO GEOLOGICAL AND METALLURGICAL PROBLEMS.

F. E. THACKWELL.

It is the major purpose of this article to direct attention to a new development in the field of microscopic analysis, which should prove of importance to progress in the scientific solution of geological, mineralogical, and metallurgical problems that are dependent upon microscopic data. This new development is in the form of an integrating stage.[1] It is simply a mechanical application of the Rosiwal[2] principle of geometric (or planimetric) analysis, which has long been known to the science of geology.

Although the device was designed primarily for rock analysis with the petrographic microscope, it is equally suitable, and has a wider application, in the field of ore-dressing. An important application of the microscope is being developed in this field for the statistical microscopic analysis of ores and mill products. The Coöperative Microscopic Laboratory of the Utah Engineering Experiment Station, University of Utah, is one of the pioneers in this work and the example of the use of the integrating stage herein cited is from one phase of this type of analysis. Publications describing two of these investigations are now in press.[3] This type of microscopic analytical work requires counting by

[1] Manufactured by E. Leitz, Wetzlar (Germany). Supplied by E. Leitz, Inc., New York City.

[2] Rosiwal, A.: Über geometrische gesteinsanalysen verhandlunger der k. k. geolog. Reichsanstalt, Wien (1898), No. 5.

[3] Head, Crawford, Thackwell, and Burgener: Microscopic Examination of Mill Products of the Copper Queen Concentrator, Phelps Dodge Corporation, Bisbee, Arizona. U. S. Bureau of Mines, Tech. Pub. 533, 1932.

Head, Crawford, Thackwell, and Burgener: Detailed Statistical Microscopic Analyses of the Ores and Mill Products of the Silver King Flotation Concentrator, Park City, Utah. U. S. Bureau of Mines, Tech. Pub. (in press), 1932.

area estimation (or by diameters) of as many as 400,000 mineral grains for a single study. Furthermore, present day ore concentration requirements are such that an average of between 50 and 90 per cent. of these mineral grains treated are of diameters less than the opening of a standard 200-mesh sieve (0.074 millimeter or 0.0029 inch). In general, samples representing the ore

FIG. 1. Microscope with integration stage attached.

in any particular investigation are prepared for counting by the usual method employed for polished section study; the relative areas of the various minerals are determined by direct area estimation, by grain count, or by summation of diameters, in any case using a travelling stage and a net ruled eyepiece; the percentage volumes are subsequently calculated; and finally, the percentage weights are computed from the specific gravities of each mineral. Finely ground mill products are sized by sedimentation and the

fractions incorporated in bakelite briquets[4] which are polished for the microscopic count as in the case of hand specimens. Accurate and detailed statistical counts are made by this procedure on material down to minus 2300-mesh in size (approximately 0.006 mm. or 0.00023 inch particle diameter). The counting of these thousands of minute particles is a lengthy, wearisome task, and involves a great deal of eye strain. The recording and totalling of the counts is in itself a tedious operation. Although the various institutions engaged in this work have made numerous improvements in technique to lessen the time and strain of microscopic counting, the nature of this phase has remained a serious handicap.

S. J. Shand,[5] as early as 1916, developed a mechanical recording micrometer (employing the Rosiwal principle) for reducing time and eye strain in counting. This stage attachment by Shand was the basis for the design of the integrating stage with which this present article is concerned. That latter attachment, developed by E. Leitz, Wetzlar (Germany), is called a "planimetric" or "integrating" stage, and was put on the market in the United States in 1931. Although primarily intended for use on a polarizing microscope, the instrument is equally adaptable to reflecting microscopes. This apparatus has six or four independent measuring spindles, with the aid of which the proportional amounts of six or four different constituents may be summed in one operation and a surface of 18 x 18 mm. planimetrically evaluated. An area of 18 x 18 mm. on an average briquet of minus 400 plus 560 mesh mineral particles, for example, contains between 5000 and 6000 individual particles. The exactness of the readings furnished by the micrometer spindles is such that within an integrating distance of 25 mm. along each component the error does not exceed 0.01 mm. The release of all the spindles causes the integrating stage to return automatically to its initial position along the measuring line, whence it may be set accurately

[4] Head, R. E. and Slavin, Morris: A New Development in the Preparation of Briquetted Mineral Grains. U. S. Bureau of Mines, Tech. Pub. 10, 1930, in cooperation with University of Utah.

[5] Shand, S. J.: A Recording Micrometer for Geometrical Rock Analyses. Jour. of Geology, vol. XXIV, pp. 394–404, 1916.

within 0.1 mm. to another line with the aid of a rack and pinion motion.

To compare the use of the integrating stage with counting as previously done, a briquetted mill product was chosen which contained only a limited number of common minerals, in appreciable quantity, so that chemical analyses were available for recombining the elements into the correct mineral composition. Thus chemical results could be used as a yard stick for comparison of the accuracy of the two counting methods. Ordinarily, the complexity of the minerals in ores and concentrator products is such that the elements determined chemically cannot be recombined to give the correct mineral composition until the quantitative ratios of the minerals are determined by the microscopic count. The conditions and results of the comparison count may be summarized as follows:

*Sample:* mill tailing from a concentrator treating a complex lead-zinc ore by differential flotation. *Particle Size:* minus 100 plus 150 mesh (average particle diameter .125 mm). *Illumination:* artificial light from a day-light bulb was employed as reflected light using a vertical illuminator. *Comparison of areas counted:* in each case, 12 equidistant, parallel strips across the surface. *Timing of counts:* total time of actual counting plus time for recording figures during the progress of the count.

| Minerals Counted | Results of count by area estimation using net ruled eye piece | | Results of count using Leitz Integrating Stage | | Chemical Results |
|---|---|---|---|---|---|
| | Number of unit areas counted | Per Cent by wt. rep. by each mineral | Micrometer spindle readings (diameters) | Per Cent by wt. rep. by each mineral | Per cent by wt. calculated from chemical analyses |
| Pyrite..... | 4068 | 16.74 | 4380 | 16.46 | 16.09 |
| Galena..... | 78 | .48 | 97 | .55 | .58 |
| Sphalerite.... | 558 | 1.84 | 680 | 2.05 | 2.39 |
| Totals... | 4704 | 19.06 | 5157 | 19.06 | 19.06 |
| | Gangue..... | 79.94 | | 79.94 | 79.94 |
| | Total.....100.00 | | | 100.00 | 100.00 |
| Time of count = 1 hr., 35 min. | | | Time of count = 50 min. | | |

*Note:* The figures in the columns above giving the percentages by weight represented by each mineral were calculated from the counts by the usual method involving multiplying by the specific gravities of each respective mineral to convert areas to weight relationships and finally into mineral composition of the sample.

SUMMARY.

In a survey of the literature in the fields of geology, mineralogy and metallurgy, it is apparent that the value of quantitative microscopic analysis has, in part, been long realized. It is also apparent that there has been marked inhibition to the use of this phase of microscopic investigation because of the tedious character of its methods of application. The new integrating stage materially reduces past objections, since it decreases counting time by approximately one half, greatly reduces eye strain and recording inconvenience, and insures a high degree of accuracy.

Although this brief comparison test of counting methods was confined to a single instance on a specific type of work, it furnishes a reliable basis for demonstrating the advantages of the integrating stage method in its general application to quantitative microscopic work. Geological or metallurgical problems (other than the ore-dressing type used for this demonstration) involve the same principle, and therefore the time factor, accuracy, and other advantages indicated in this case are undoubtedly equally applicable. All the conditions encountered in the technique of planimetric microscopic counting in a complete analysis, or a more complex problem, were involved.

This new mechanical stage development should aid in adding impetus to the general use of quantitative microscopic analytical studies, and it is believed timely to offer these observations for the purpose of directing the attention of researchers in geological and metallurgical sciences to the subject.

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# DISCUSSION AND COMMUNICATION

## *MAGMATIC CHROMITE DEPOSITS IN SOUTHERN AFRICA.*

*Sir:* It was with feelings of pleasure that I read the recent paper by Edward Sampson [1] dealing with the chromite deposits of South Africa and Southern Rhodesia, particularly so inasmuch as about two years ago I was forced to express my disagreement [2] with several of Dr. Sampson's conclusions expressed in an earlier paper dealing in part with the same subject.[3]

In the paper most recently published Dr. Sampson has apparently partially abandoned his earlier views that the manner of occurrence of chromitite in the Bushveld Complex points to the likelihood of " the chromite being in a residual solution " [3] of the magma which formed the associated silicate rocks. His ideas as expressed latterly appear to me to be in accord with the field relationships of the chromite bands in the Great Dike and in the Bushveld Complex, and agree with those which I expressed in 1930.[4] He goes a stage further than I did by suggesting refusion of the sorted chromite crystals in order to explain the detailed relations between the chromite and the silicate crystals. There are many objections to such a process having taken place, as the author of the paper points out, but to my mind there are far greater objections to his earlier or second theory involving " the simultaneous formation of chromite and silicate from a residual solution "!

In the Umvukwe area of the Great Dike it is shown [4] that there are at least seven seams or bands of high grade chromite rock

[1] Sampson, Edward: Magmatic Chromite Deposits in Southern Africa. ECON. GEOL., vol. 28, pp. 113–144, 1932.

[2] Keep, F. E.: Discussion, ECON. GEOL., vol. 25, pp. 219–221, 1930.

[3] Sampson, Edward: May Chromite Crystallize Late? Ross, C. S.: Is Chromite Always a Magmatic Segregation Product? ECON. GEOL., vol. 24, pp. 632–649, 1929.

[4] Keep, F. E.: The Geology of the Chromite and Asbestos Deposits of the Umvukwe Range, Lomagundi and Mazoe Districts. So. Rhod. Geol. Survey, Bull. 16. Salisbury, 1930.

separated from one another by from 125 to 1700 feet of serpentine rock and occurring in more or less parallel planes. It is difficult to believe that these seams could have been formed by "an actual intrusion of a chromite-rich magma."

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JOHANNESBURG,
SOUTH AFRICA.

## *SIXTEENTH INTERNATIONAL GEOLOGICAL CONGRESS.*

The third circular of the Congress has now been issued, giving full particulars as to meetings, excursions, and costs. The Congress meets in Washington from July 22 to July 29. The excursions to various parts of the Eastern United States last from four to twelve days, and include a transcontinental excursion from San Francisco to Washington for the benefit of those coming from the West. Alternate days during the sessions will be given to short excursions around Washington.

The post-congress excursions include two transcontinental excursions, each lasting 31 days, and two shorter trips, one to study glacial geology in the Central States, the other to study pre-Cambrian geology and the iron and copper deposits of the Lake Superior region.

The larger excursions are being run below cost through the generosity of the Geological Society of America.

The special topics for the sessions are: Measurement of Geologic Time by Any Method; Batholiths and Related Intrusives; Zonal Relations of Metalliferous Deposits; Major Divisions of the Paleozoic Era; Geomorphogenic Processes in Arid Regions; Fossil Man and Contemporary Faunas; Orogenesis; Geology of Petroleum; Copper Resources of the World.

Membership in the Congress is open to any one interested. Individuals who cannot attend, and institutions, are advised to send in the membership fee of $5.00 in order to obtain without further charge the valuable set (over 30) of guide books that relate to the geology of the regions covered by the excursions.

For further information address: W. C. Mendenhall, General Secretary, U. S. Geological Survey, Washington, D. C.

# REVIEWS

**The Genesis of the Diamond.** By ALPHEUS F. WILLIAMS. 2 vols. Pp. 676, pls. 229. Ernest Benn, Ltd., London, 1932. Price £4 4 s.

It was a fortunate coincidence for the science of geology that brought a man of ingenious scientific mind into active diamond operations. Mr. Alpheus Williams, first as consulting engineer to a number of diamond companies, and then succeeding his father Mr. Gardner Williams, himself an able student of the diamond, as general manager of the De Beers diamond mines, has had unparalleled opportunity to study the diamond and its occurrence. Thousands of carats annually passed through his hands. He studied their crystallography, photographed them, cracked many open, and sliced them. He learned their secrets before they passed into the channels of commerce. For many years also he has studied closely the kimberlite host rock, and the diamond pipes with their fascinating inclusions. These features are treated exhaustively in his two large volumes. In addition he tells of the practice of mining and recovery, the kimberlite dikes and fissures, the alteration of the kimberlite, and the diamond-bearing gravels of South Africa. The 676 pages are filled with interesting information, most of it new. Particularly outstanding are his contributions to the occurrence and origin of the kimberlite and the pipes, the petrographical and chemical study of the inclusions in the pipes, and the crystallography and origin of the diamond.

The author concludes that the pipes are not explosive volcanoes but are localized by intersecting fissures formed by disruption, perhaps by the release of gases. He advances strong arguments to show that these pipes were filled with broken rubble from the walls and overlying rocks before the magma was intruded. Then came a slow, quiet upwelling of magma, with a low temperature of crystallization, that engulfed the already broken fragments, affecting them hardly at all. This kimberlite magma, he concludes, came from a deep magmatic reservoir and represents the differentiation residual after the solidification of peridotite, pyroxenite, and eclogite. He holds the possibility, however, that it may in part represent the fusion of earlier formed peridotite and eclogite.

The inclusions, which constitute a considerable part of the pipe filling, he divides into two groups,—accidental, or those derived from wall rocks, and cognate, or those born within the magma. The accidental inclusions

range from minute, delicate wisps of shale to blocks 1000 feet high. Some (granite) inclusions have been carried up to heights of 2700 feet above their original site; and surface rocks have been found to depths of 2500 feet. Some of these are fragile fragments of light shale which, he points out, could not have sunk in a basic magma. They were there before the magma came in. Some fragments contain fossil wood and vertebrates.

The cognate inclusions consist of kimberlite, peridotites, pyroxenites, and eclogites which, with the diamonds, garnets, and other minerals, have been brought up from great depths. His detailed petrographical study of these interesting inclusions is supplemented by a great many new rock analyses, and by excellent photomicrographs, comprising 32 beautifully colored plates.

With respect to the origin of the diamonds, he dismisses the possibility of their having been formed *in situ*, or having crystallized in the eclogite from which they were derived by fusion, and concludes that they crystallized in the original kimberlite magma and were carried up into the pipes as already formed crystals. Two neat bits of evidence are advanced to support this—(1) that two pieces of a finger-shaped diamond found in different parts of the De Beers pipe fitted together exactly, showing that the diamond was not formed *in situ* but was transported from below, and (2) that the diamond contains inclusions of minerals foreign to the kimberlite but characteristic of the deeper-seated rocks.

These two volumes, in the opinion of the reviewer, represent the most outstanding work on the diamond and its occurrence that has been produced or is likely to be produced, since no one with Mr. Williams' scientific bent and knowledge has ever had the urge and the opportunity to carry through the observations, chemical analyses, and petrographic studies that he has made. In view of the outstanding contributions, one can excuse the poor arrangement of material, the abundant repetition, the long quotations, the size, large beyond necessity, and the difficulty of reference.

The book is pleasingly produced, beautifully illustrated, interesting to any reader, and one that should be in every library. Science owes a debt of gratitude to Mr. Alpheus Williams.

ALAN BATEMAN.

**La Géologie et les Mines de la France d'outre-Mer.** By a committee under the direction of M. A. LACROIX. Pp. 604, pls. 2, figs. 38. Paper, 9½ x 6¼. Société d'Éditions Geographique, Maritimes et Coloniales, Paris, 1932.

This is one of a series of volumes designed mainly to bring to the notice of the public the resources of the French Colonies. The present report

is a sort of symposium on the geology and mining industry of Algeria, Tunisia, Morocco, Algerian Sahara, French West Africa and Togo, French Equatorial Africa and Cameroun, French Somaliland, Madagascar and neighboring islands, Reunion, States of the Levant under French mandate, French Indo-China, New Caledonia, New Hebrides and Iles Wallis, French Oceania, Martinique and Guadaloupe, French Guiana and a few smaller possessions, mainly scattered islands. Each article was written by a man who is regarded as an authority on the district discussed by him, and many of the authors are widely known. The stratigraphy and tectonics of each colony are given in as full detail as present knowledge warrants, followed by an account of its mineral deposits, a discussion of the economic conditions under which they exist, and finally by a bibliography of important publications dealing with the colony. Most of the articles are illustrated with sketch maps and cross-sections, and many of them with black and white geological maps. There are also three geological maps on plate paper that cover comparatively large areas.

The concluding chapter (50 pages) by L. Bertrand is devoted to a general account of the nature and origin of petroleum and the conditions under which commercial accumulations are known to occur, and to a study of the geology of the different colonies to discover, if possible, whether such favorable conditions exist in any of them. In addition, a brief discussion of the petroleum possibilities of Mesopotamia and Syria is given because of France's one-fourth interest in the production of these countries. The result is not of a very optimistic character. It is not believed that the French Colonies will ever produce a large quantity of oil, but it is believed that in Northern and Equatorial Africa, Madagascar and New Caledonia conditions are such as to justify thorough exploration.

W. S. BAYLEY.

**The Geology and Water Resources of Northwestern Minnesota.** By IRA S. ALLISON. Pp. 245, figs. 96. Minn. Geol. Survey Bull. 22. University of Minnesota Press, Minneapolis, Minn. Price, $1.00.

The report covers geology and water supply of twenty-six counties in northwestern Minnesota, comprising about one third of the State. The general geology and the chemical compositions of the waters found in the area are briefly considered, followed by a description of the general features, surface deposits, solid rock formations, head of water, and quality of water for each of the counties in the region.

M. H. BILLINGS.

**Ergebnisse Geologischer Forschungen in Minas Geraes (Brasilien).** By PROFESSOR DR. B. VON FREYBERG. Pp. 404, figs. 53, pls. 27, including 2 colored maps. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1932. Price, (paper), 52 M.

Although Minas Geraes has long been noted for its production of diamonds, its geology is almost unknown. The author of the present volume has attempted to fill in some of the space on the geological map of the State by making a number of trips across the area, which in all aggregate about 2000 Km. As the result of these travels he has been able to give us an outline of the State's geology which is much more complete than anything of the kind that we have had heretofore.

As one advances inland from the coast in a northwesterly direction, he crosses a sand-covered coastal strip, and beyond that a strip of Tertiary rocks, that slopes upward until it passes suddenly into the steeper slopes of the coastal mountains (Serra do Mar) composed mainly of gneisses and granite. These heights constitute the border of a plateau that stretches far to the northwest beyond the borders of the State. The Serra do Mar gradually rise into the higher and more rugged Serro do Espinhaço, which are composed of folded and faulted members of the Minas and the Itacolumy series. Beyond to the west follow the almost horizontal members (Geraes schists) of the Bambuhy series of bedded rocks, which farther to the northwest become folded and are known as the Indayá schists. Unconformably over the Bambuhy series are the horizontal members of the Gondwana series, forming table lands.

According to the author the gneisses and granites of the Serra do Mar are Archean. Over this unconformably are the quartzites, slates, marbles and iron ores of the Minas series, which are probably Algonkian, and unconformably over these is the Itacolumy series of quartzites, conglomerates and a few schists that are either upper Algonkian or Cambrian. The Bambuhy series is thought to be Silurian or Devonian; though no discordance has been discovered between it and the underlying beds. The series consists of quartzites, quartzitic schists, slates and limestones. Unconformably above the Bambuhy is the Triassic Gondwana series of red sandstone, and unconformably above this, the Baurú and the Uberaba series of light sandstone and tuffs, which are recognized as Cretaceous. Above these are Tertiary beds that have been given no distinctive name. The Cretaceous and Triassic series are cut by basic volcanic rocks. The Bambuhy series contains veins of galena. The three lowest series are intruded by pegmatites, granites and basic dikes and contain basic igneous sheets.

Each of the series mentioned above is described in detail. The histories of the terms are outlined and the reasons for the acceptance of those used are given. All the members of the Minas series are more or

less metamorphosed, one form—the well known itacolumite—being a sandy quartzite containing talc and chlorite. Among the economic phases of the series are jacutinga and the iron ores (itabirites) described by Leith and Harder, gold, barite, bauxite, manganese ores, topaz and cinnabar. Most of these materials are in the neighborhood of Ouro Preto. In his discussion of the Gondwana series the author calls attention to the presence of basic intrusives, some in the form of pipes, in which it is possible that the diamonds of the region may have had their sources.

A large part of the volume is devoted to the structure and physiography of the State and to its river system. Many fairly detailed geological maps and structure profiles of important small areas are scattered through the book, and it concludes with a bibliography numbering 976 items. Unfortunately there is no index.

W. S. Bayley.

**Internationaler Geologen und Mineralogen Kalender.** Rudolph Cramer. Deutsche Geologische Gesellschaft. Ferdinand Enke, Stuttgart, December, 1932 (dated 1933).

This book is a directory of geologists and mineralogists, geological surveys and allied institutions, university geological departments, museums with geological departments, geologic and associated societies. Part I gives the names and addresses of about 7,000 geologists. Part II lists the state geological and allied surveys of the world, the address of each survey, its staff, each man's rank and specialty, publications issued by the survey, the sales agent for the survey publications. Part III lists the universities, colleges, mining schools, museums of the world, which have geological departments, the staff of each, and each man's rank and specialty. Part IV lists the geological and associated societies of the world with the address of each; also for many of the societies: the secretary or officers, the publications issued by the society, and its dues.

The reviewer's copy of the preceding (1925–26) edition of the Geologen Kalender has been highly valued and frequently referred to, and he will have much use for this excellent revised edition, which seems reasonably correct and up to date. It is most convenient to be able to pick up a single volume and to see whether such and such a State has a geological survey, what its official title is, where its headquarters are, who its director it, who is professor of geology, paleontology, etc., at a university, or what is the address of such and such a foreign geologist.

Donald C. Barton.

## BOOKS RECEIVED.

By

DAVID GALLAGHER.

**Heat Transmission Through Building Materials.** By F. B. Rowley and A. B. Algren. Pp. 106, tables 14, figs. 63. Univ. of Minnesota, Bull. No. 8. Minneapolis, 1932. Complete and comprehensive treatment of theory, apparatus, and tests, with special reference to walls.

**Meteorites Found in Pennsylvania.** By R. W. Stone. Pp. 28, figs. 14. Penn. Topog. and Geol. Surv., Bull. G–2, 1932.

**Chemical Character of Surface Water of Virginia.** By W. D. Collins, E. W. Lohr, K. T. Williams, H. S. Haller, and O. C. Kenworthy. Pp. 148, pls. 1, figs. 7. Comm. of Virginia, Div. of Water Resources and Power, Bull. No. 3. Richmond, 1932.

**Pegmatite Deposits of Virginia.** By A. A. Pegau. Pp. 123, pls. 20, figs. 11, tables 9. Virginia Geol. Surv. Bull. 33. University, Va., 1932. Geology of the region, consideration of pegmatites in general, descriptions of the geology of the individual pegmatites of this famous mineral region.

**The Bushveld Igneous Complex of the Central Transvaal.** By A. L. Hall. Pp. 560, pls. 41, figs. 40. Union of South Africa Geol. Surv. Mem. 28. Pretoria, 1932. Price, 10/—. A monumental work by the man whose intimate knowledge of the Bushveld is unparalleled.

**Index to the Memoirs of the Geological Survey of India,** Volumes I–LIV, 1859 to 1929. By T. H. D. La Touche. Pp. 431. Government of India, Central Publication Branch, Calcutta, 1932. Price, Rs. 6–4, or 10s. A most detailed and complete index of authors, subjects, authorities, and figured sections of this great group of publications.

**Borates.** Second edition, 1920–1932. Pp. 44. Imperial Institute, London, 1933. Price, 9d. General, properties, uses, production and prices, world occurrences described by countries, bibliography.

**Black Marbles of Northern Arkansas.** By B. Parks, J. M. Hansell, and E. E. Bonewits. Pp. 51, pls. 5, figs. 16, tables 8. Ark. Geol. Surv., Information Circular 3. Little Rock, 1932. Price, $1.10. Geology and properties of these marbles, with special attention to their economic possibilities.

**Phosphat—Nitrat.** By O. Stutzer and W. Wetzel. Pp. 390, figs. 101, tables 3. Die Wichtigsten Lagerstätten der "Nicht-Erze," Band IV. Gebrüder Borntraeger, Berlin, 1932. Price, 32 RM; bound, 34 RM.

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The recently published 20-volume index (336 pages) of Economic Geology for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.

# SCIENTIFIC NOTES AND NEWS

Friedrich Ahlfeld, of Marburg, Germany, has been investigating the Central Asia ore deposits in Taschkent, U. S. S. R.

Douglas A. Greig, of London, England, is at Formovo-Taro (Parma), Italy, as geologist for the Societa Petrolijera Italiana, under the Standard Oil Company of New Jersey.

Leslie A. Fisher, geologist, Sinclair Prairie Oil Co., has been transferred from Tyler to Fort Worth, Texas.

Hans Stille, formerly connected with the Geological Institute at Göttingen, is now director of the Institute of Geology and Paleontology at Berlin.

Frank Ayer recently resigned as manager of the Morenci Branch of Phelps-Dodge, to become general manager of Roan Antelope Copper, Northern Rhodesia, in place of D. D. Irwin, resigned.

W. P. Alderson and A. A. McMartin, of Montreal, have gone to Africa to examine properties in the Kakamega gold field, Kenya, for Canadian interests.

Charles A. Mitke is engaged in examining mines in Mexico.

Sir Douglas Mawson, professor of geology at the University of Adelaide, is visiting England.

Robert W. Karpinski has returned to Ann Arbor, Mich., after an extended reconnaissance trip in Alaska for a syndicate in Detroit.

Angus McLeod, geologist for the Shell Petroleum Corporation at Dallas, is now located at Houston, Texas.

W. H. Haas is now acting chairman of the Department of Geology and Geography at Northwestern University.

Raymond M. Larsen, of the U. S. Geological Survey, spent several months during last fall in geological and engineering work at the Cedar Creek anticline near Baker, Montana, and was later transferred to Thermopolis, Wyoming.

E. R. Scott has joined the staff of the Department of Geology, University of North Carolina, Chapel Hill, N. C.

The Oklahoma City Geological Society has elected for 1933 the following officers: president, Baxter Boyd; vice-president, H. S. Thomas; secretary-treasurer, G. C. Maddox; recording secretary, E. I. Thompson.

The Fort Worth Geological Society has elected for the coming year the following officers: president, Walter R. Berger; vice-president, R. H. Fash; secretary-treasurer, Lewis C. Roberts.

Irwin Roman, formerly of the Geophysical Research Corporation and now assistant professor of mathematics and physics at the Michigan College of Mining and Technology, has invented an equipment for inspection of drill holes, namely, a tubular casing to be lowered into the drill hole; two magnetic compasses, one near the bottom and the other near the top of the tube; an incandescent lamp with a lens producing parallel rays of light through the tube; and a recording device in the top of the tubular casing.

E. Leitz, Incorporated, are offering a new instrument for the determination of the refractive indices of minerals to the fourth decimal place, with the use of only thirteen liquids, instead of the fifty-five or more usually required for the purpose, and a new simplified universal rotating stage having only two axes of rotation. Both instruments are welcome additions to petrographic apparatus.

The American Association of Petroleum Geologists will hold their 18th annual meeting in Houston, Texas, on March 23–25, with headquarters at the Rice Hotel. Two field trips are to be taken, one to Conroe Oil Field on the afternoon of March 25, and the other to the Sugarland field and the sulphur mine at New Gulf in Wharton County (cost, $2.00) on March 26. For additional information, address Alexander Deussen, chairman of General Committee, 1606 Dispatch Building, Houston, or John Vetter, Rio Bravo Oil Company, Houston.

Recent visiting lecturers in geology at Northwestern University, Evanston, Ill., included: T. A. Hendricks, U. S. Geol. Survey, on Classification of Coal; L. E. Workman, Illinois Geol. Survey, on Subsurface Methods as applied to Illinois; C. W. Washburne, on Structural Studies in the Oregon Coast Ranges; E. S. Bastin, University of Chicago, on Ores of Copper Lean in Iron and Sulphur.

A correction: In Bulletin 58 of the National Research Council, page 59, in a review of geological work done in Minnesota, there is an implication that little work was done in Minnesota between 1872 and 1900. This should read "between 1900 and 1912," for, as most American geologists will recall, the State Geological Survey under the able direction of N. H. Winchell issued between 1872 and 1900 a fine series of reports, including 24 annual reports, 10 bulletins, and a six-volume series entitled the Final Report of the Survey.

Arthur Gray Leonard, professor of geology at the University of North Dakota, and State Geologist for thirty years, died at his home in Grand Forks on December 17, 1932.